

Physics 200B Lab 5: Force and Motion

“... *equal forces shall effect an equal change in equal bodies* ...”

- Newton

Objectives

- To develop a method for measuring forces reliably.
- To explore how the motion of an object is related to the forces applied to it.
- To examine the mathematical relationship between force, mass, and acceleration—Newton’s second law.

OVERVIEW

In the previous labs, you have used a motion detector to display position-time, velocity-time, and acceleration-time graphs of different motions of various objects. You were not concerned about how you got the objects to move, i.e., what forces (pushes or pulls) acted on the objects. From your own experiences, you know that force and motion are related in some way. To get your something moving, you (or something) must push on it. But exactly how is force related to the quantities you used in previous labs to describe motion: position, velocity, and acceleration?

In this lab you will pay attention to forces and how they affect motion. You will first develop an idea of a force as a push or a pull and see how to measure forces. Next, by applying forces to a cart and observing the nature of its resulting motion graphically with a motion detector, you will come to understand the effects of forces on motion.

INVESTIGATION 1: MEASURING FORCES

In this investigation you will explore the concept of a constant force and the combination of forces in one dimension. You can use these concepts to learn how to measure forces with a force probe.

Activity 1-1: Measuring Forces with a Force Probe

1. Plug the force probe into Channel 1 of the computer interface. Display force vs. time axes by opening the experiment file called **Measuring Force (L3A1-2a)**.

Change the sensitivity setting of the force probe to 50 N and then click on the LabPro icon and change Channel 1’s properties to Force- dual range (50 N).

Comment: Since forces are detected by the computer system as changes in an electronic signal, it is important to have the computer “read” the signal when the force probe has no force pushing or pulling on it. The computer then adds or subtracts whatever signal it measures so that the reading with no force is 0.000 N. This process is called “zeroing.” Also, the electronic signal from the force probe can change slightly from time to time as the temperature changes. Therefore, it is a good idea to **zero** your force probe with nothing attached to the probe before making each measurement.

2. **Zero** the force probe with nothing pulling on it.

3. Have someone hold one end of a rubber band fixed, and attach the other end to the force probe hook. Pull horizontally on the rubber band with the force probe until the band is stretched 1 cm and begin graphing while holding the rubber band steady for the whole graph.

Use the **analysis feature** of the software (select the appropriate region of the graph, then Analyze/Statistics) to get an accurate reading of the force.

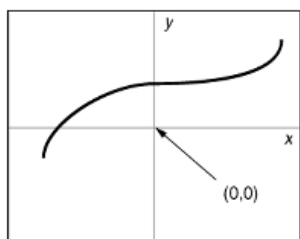
Record the force probe reading with its uncertainty (mean and standard deviation): _____

4. Now you'll measure the force exerted by multiple rubber bands. The easiest way to take these data is to open the experiment file called **Rubber Bands (L3A1-2b)**. This experiment sets the software in **event mode** and plots the measured force against the number of rubber bands.

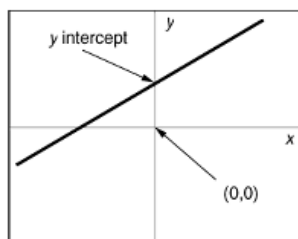
Zero the force probe and then begin graphing. The force probe reading will be displayed at the bottom of the graph (in a small window) continuously until you decide to **keep** the value.

Keep the force value with 0 rubber bands, and enter 0 when prompted; then attach 1 rubber band to the force probe and pull it to 1 cm, **keep** the reading, and enter 1. Repeat with 2, 3, and 4 rubber bands pulled to 1 cm. Click on **Stop** to when you are done.

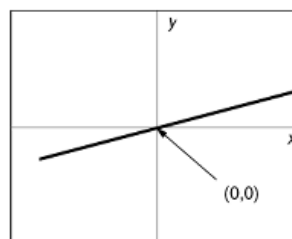
Comment: We are interested in the nature of the mathematical relationship between the reading of the force probe and the force in rubber band units. This can be determined from the graph by drawing a smooth curve that fits the plotted data points. Some definitions of possible mathematical relationships are shown below. In these examples, y might be the force probe reading and x the number of rubber bands.



y is a function of x , which increases as x increases.



y is a *linear* function of x , which increases as x increases according to the mathematical relationship $y = mx + b$, where b is a constant called the *y intercept*.



y is proportional to x . This is a special case of a linear relationship where $y = mx$, and b , the *y intercept*, is zero.

These graphs show the differences between these three types of mathematical relationships. *Proportionality refers only to the special linear relationship where the y intercept is zero, as shown in the example graph on the right.*

5. **The fit routine** of your software (under Analyze) allows you to determine the relationship by trying various curves to see which best fits the plotted data. Try a linear fit: $F = c + bx$ and any other that you think is appropriate.

Question 1-1: Is the mathematical relationship between force probe reading and number of rubber bands proportional? Explain your reasoning.

Question 1-2: Based on your graph, what force probe reading would probably correspond to the pull of five rubber bands when stretched to 1 cm? How did you determine this?

Comment: Your graph relates two different ways of measuring force, one with a standard stretch of different numbers of rubber bands (rubber band units) and the other with a force probe. Such a graph is called a calibration curve and is used to compare measurements of quantities made with two different measuring instruments. You could use it to convert forces measured in force probe units to rubber band units, and vice versa.

Physicists have defined a standard unit of force called the *Newton*, abbreviated N. For the rest of your work on forces and the motions they cause, it is convenient to have the force probe read directly in newtons. Fortunately, the force probe has been calibrated at the factory to do so!

! Checkpoint 1

INVESTIGATION 2: MOTION AND FORCE

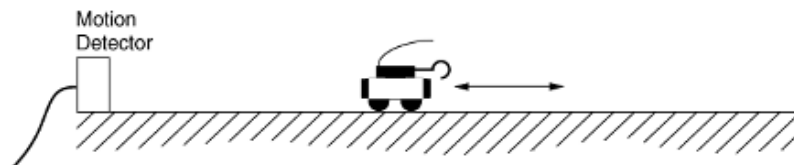
Now you can use the force probe to apply known forces to an object. You can also use the motion detector, as in the previous two labs, to examine the motion of the object. In this way you will be able to explore the relationship between motion and force.

Activity 2-1: Pushing and Pulling a Cart

In this activity you will move a low friction cart by pushing and pulling it with your hand. By measuring the force, velocity, and acceleration, you will be able to look for mathematical relationships between the applied force and the velocity and acceleration.

1. Set up the cart, force probe, and motion detector on the track as shown below.

The force probe should be fastened securely to the cart so that its body and cable do not extend beyond the end of the cart facing the motion detector. (If you wish, tape the force probe cable back along the body to assure that it will not be seen by the motion detector, or hold the cable loosely over the cart.)



Suppose you grasp the force probe hook and move the cart forward and backward in front of the motion detector. Do you think that either the velocity or the acceleration graph will look like the force graph? (That is to say, if you apply a changing force to the cart, will the velocity or acceleration change in the same way as the force?)

2. Open the experiment file called **Motion and Force (L3A2-1)**. This will set up velocity, force, and acceleration axes.

If necessary, change the sensitivity setting of the force probe to 10 N and then click on the LabPro icon and change Channel 1's properties to Force-dual range (10 N).

3. Zero the force probe (don't zero the motion detector). Grasp the force probe **by the hook** and begin graphing. When you hear the clicks, quickly pull the cart away from the motion detector and abruptly stop it. Then quickly push it back toward the motion detector and again abruptly stop it. Pull and push the force probe hook along a straight line along the ramp. Do not twist the hook. *Be sure that the cart never gets closer than 0.5 m to the motion detector.*

4. Change the scale of the graphs to make them easier to see, if necessary.

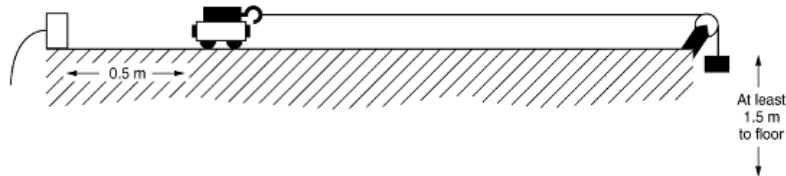
Question 2-1: Does the velocity-time graph resemble the force-time graph? Does the acceleration-time graph resemble the force-time graph?

Activity 2-2: Speeding Up Again

You have seen in the previous activity that force and acceleration seem to be related. But just what is the relationship between force and acceleration?

Prediction 2-1: Suppose that you have a cart with very little friction and you pull this cart with a constant force (force vs. time is a horizontal straight line). Describe the predicted shape of the velocity vs. time and acceleration vs. time graphs, and sketch their shapes below.

1. Test your predictions. Set up the ramp, pulley, cart, string, motion detector, and force probe as shown below. Add 200 g of mass to the cart. Attach a 50 g object to the other end of the string. Be sure that the ramp is level.



2. Prepare to graph velocity, acceleration, and force. Open the experiment file called **Speeding Up Again (L3A2-2)** to display velocity, acceleration, and force axes.

3. Test to be sure that the motion detector sees the cart during its complete motion. *Remember that the back of the cart must always be at least 0.5 m from the motion detector.*

4. **Zero** the force probe with the string hanging loosely so that no force is applied to the probe. Be sure to **zero** it again *before each graph*.

5. **Begin graphing.** Release the cart after you hear the clicks of the motion detector. Be sure that the cable from the force probe is not seen by the motion detector, and that it doesn't drag or pull the cart. You may need to hold the cable up in the air over the moving cart. Stop the cart with your hand before it reaches the end stop.

Repeat until you get good graphs.

6. If necessary, adjust the axes to display the graphs more clearly. Use the **statistics feature** of the software to measure the average force and average acceleration for the cart (with standard deviations), and record your measured values in the second column of the table on the next page. *Find the mean values only during the time intervals when the force and acceleration are nearly constant.*

Question 2-3: During the time after the cart has started moving but before it slows to a stop, is the force that is applied to the cart by the string constant, increasing, or decreasing? Explain based on your graph.

Question 2-4: How does the acceleration graph vary with time during the time after the cart has started moving but before it slows to a stop? Does this agree with your prediction?

Question 2-5: Does it appear that a constant applied force produces a constant velocity, or a constant acceleration?

! Checkpoint 2

Activity 2-3: Acceleration From Different Forces

In the previous activity you examined the motion of a cart with a constant force applied to it. But what is the relationship between acceleration and force? In this activity you will try to answer these questions by applying different forces to the cart, and measuring the corresponding accelerations. You can then plot a graph of acceleration vs. force and find the mathematical relationship between acceleration and force (with the mass of the cart kept constant).

1. Accelerate the cart with a larger force than before. To produce a larger force, hang a 100 g object from the string.

2. Graph force, velocity, and acceleration as before. *Don't forget to zero the force probe (with nothing attached to the hook) right before graphing.*

3. Use the **statistics feature** of the software to measure the average force and average acceleration for the cart for this activity, and record your measured values in the table below. *Find the mean values only during the time intervals when the force and acceleration are nearly constant.*

4. Accelerate the cart with 150 g of hanging mass. Graph velocity, acceleration, and force. Find the mean acceleration and force, as before, and record the values in the last column of the table.

hanging mass (g)	50	100	150
Mean force (N) and uncertainty			
Mean acceleration (m/s ²) and uncertainty			

Question 2-6: Compare the forces exerted on the cart by the 50 g object and the 150 g object. The two masses are in a ratio 1:3. Are the two forces in a ratio 1:3? (They shouldn't be. This is a puzzle we'll solve later.)

5. Use the **graphing routine** in the software to plot a graph of force vs. acceleration from the data in the table above. To plot the graph load the experiment file called **Acceleration vs. Force (L3A2-5)**, and **enter** your data in the table. Adjust the graph axes, after all of the data are entered, to best display the data. Make sure Avg. Force is on the vertical axis and Avg. Accel. is on the horizontal axis-click on the axis label to change.

6. Use the **fit routine** to determine the mathematical relationship between the acceleration of the cart and the force applied to the cart as displayed on your graph.

Question 2-7: What is the mathematical relationship between the acceleration of a cart (with fixed mass and negligible friction) and the force applied to the cart (measured by the force probe mounted on the cart)? Write down the equation you found and describe the mathematical relationship in words.

! Checkpoint 3

INVESTIGATION 3: FORCE, MASS AND ACCELERATION

In previous activities you have applied forces to a cart having the same mass and examined its motion. But when you apply a force to an object, you know that the object's mass has a significant effect on its acceleration. For example, compare the different accelerations that would result if you pushed a 1000-kg (metric ton) automobile and a 1-kg cart with the same force! In this investigation you will explore the mathematical relationship between acceleration and mass when you apply a known force to carts of different mass.

Activity 3-1: Acceleration and Mass

Use the electronic scale to measure the total mass of the cart including the force probe and the 200 g mass you had on top.

mass of cart + probe + 200 g mass:

Now remove the 200 g mass and add a 500 g mass to the cart.

mass of cart + probe + 500 g mass:

Open the experiment file called **Acceleration & Mass (L5A1-1)**.

1. Zero the force probe with no force on it. Now set up with the 50 g hanging mass. Let the cart go and graph the motion. Measure the average force and average acceleration of the cart *during the time interval when the force and acceleration are nearly constant* and record these values in the first column of the table below.

Data for cart+probe+500 g mass:

hanging mass (g)	50	100	150
Mean force (N) and uncertainty			
Mean acceleration (m/s^2) and uncertainty			

2. Repeat for the other two hanging masses you used in Activity 2-3. Measure the average force and acceleration of the cart, and record these values in the table.

Activity 3-2: Relationship Between Acceleration and Mass

1. Plot a graph of applied force (vertical) vs. average acceleration (horizontal). Adjust the axes to best display the data.

Question 3-1: For the same applied force, is the acceleration of the cart greater, smaller, or the same if a larger mass cart is used? Explain, using your graphs from this activity and Activity 2-3.

2. Use the **fit routine** in the software to fit the data on your graph of force vs. acceleration.

Question 3-2: Write down the slopes and their uncertainties of the best-fit lines for this activity and for activity 2-3.

Activity 3-2 (cart + probe + 500 g):

Activity 2-3 (cart + probe + 200 g):

Comment: These slopes are force/acceleration ratios (assuming that you've plotted force on the vertical axis, and that the y-intercept of the graph is close to zero). Physicists call the quantity you have just calculated—the ratio of total force on an object to its acceleration—the *inertial mass* of the object. You could continue to determine and compare masses by accelerating them and taking force to acceleration ratios, but this process is pretty tedious. A simpler approach is to use an electronic scale or a mechanical balance that has already been calibrated in kilograms by somebody using a standard mass! (The details of why such devices can give us correct masses in kilograms will not be easy to understand fully until after gravitational forces are studied.)

Question 3-3: Compare the inertial masses you determined from the slopes of the F vs. a graphs (in Question 3-2) to the masses you measured with the electronic scale (at the beginning of Activity 3-1). Do you agree that they seem to be measuring the same thing?

Comment: In your experiments, you have seen that the physical quantities force, mass and acceleration are related. In the activity you have just done, you have used this relationship to *define* inertial mass in terms of *standard* units of force, length, and time. This is a good logical definition of inertial mass.

Historically, however, the units of mass, length, and time were defined first as *standards* and the unit of force was defined as a *derived* unit in terms of these standard units. Thus, a *Newton of force is defined as the force needed to accelerate 1.00 kg at 1.00 m/s².*

! Checkpoint 4

INVESTIGATION 4: SIGNS OF FORCE, ACCELERATION, AND VELOCITY

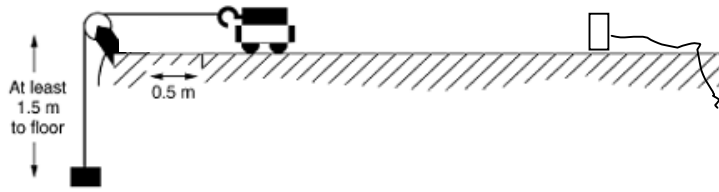
Activity 4-1: Speeding Up and Slowing Down

In previous part of the lab you looked at cases where the velocity, force, and acceleration vectors had the same sign (that is, they all pointed in the same direction). For example, if the cart is moving toward the right and a force is exerted toward the right, then the cart will speed up. The acceleration is also toward the right. The three vectors can be represented as



If the positive x direction is toward the right, then you could also say that the velocity, acceleration, and force are all *positive*. In this investigation, you will examine the vectors representing velocity, force, and acceleration for a more complicated motion of the cart.

1. Set up the cart, ramp, pulley, hanging mass, and motion detector as shown in the diagram that follows. Use a hanging mass that causes the cart to move all the way across the ramp from right to left in about 2–3 s when the mass is released (about 50 g).



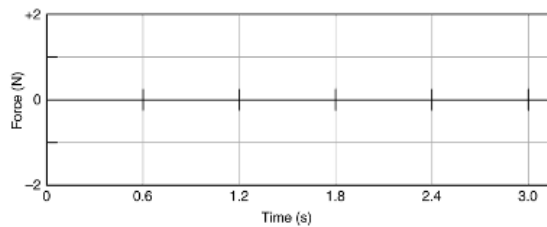
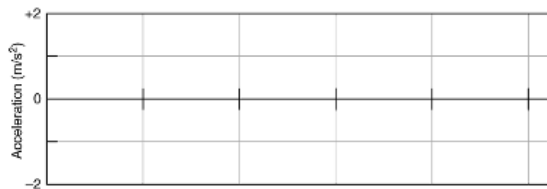
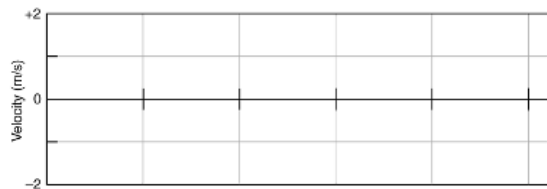
Now when you give the cart a push toward the motion detector, release it, and let it move away, it will slow down, reverse direction, and head back away from the motion detector. As usual, the positive x direction is chosen to be away from the motion detector—toward the left.

2. Test to be sure that the motion detector sees the cart during its complete motion, and that the string and force probe cable are not interfering with the motion detector or the motion of the cart. Remember that the cart must always be at least 0.5 m from the motion detector.

Prediction 4-1: Sketch on the axes that follow with dashed lines your predictions for the velocity, acceleration, and force during the time after the cart leaves your hand and before you stop it. Mark on your prediction the time at which the cart reverses direction.

Also predict directions (+, -, 0) for the velocity, force and acceleration at the following times:

- While the cart is moving toward the motion detector: v: a: F:
- As the cart reverses direction: v: a: F:
- While the cart is moving away from the motion detector: v: a: F:



4. Open the experiment file **Slowing Down Again (L4A1-1)**. As always, **zero** the force probe with nothing pulling on it just before each graph. Begin graphing, and when the motion detector starts clicking, give the cart a short push toward the right and then let it go. *Be sure to keep your hand out of the region between the motion detector and the cart.* Stop the cart before it hits the pulley.

Sketch your observed graphs with solid lines on the axes above. Mark on your graphs the time at which the cart reverses direction.

Question 4-1: Did the graphs of the velocity, force, and acceleration agree with your predictions? If not, can you now explain the graphs?

Question 4-2: Describe the force and acceleration at the moment when the cart reverses direction. Based on your knowledge of acceleration and force, explain why the force and acceleration have the signs they have at the moment the cart reverses direction.

Question 4-3: After you released the cart, was the force applied by the falling mass constant, increasing, or decreasing? Explain why this kind of force is necessary to cause the observed motion of the cart.

Question 4-4: After you released the cart: Is the direction of the velocity always the same as the direction of the force? Is the direction of the acceleration always the same as the direction of the force? In terms of its magnitude and direction, what is the effect of a force on the motion of an object?

! Checkpoint 5