CBL Lab

Free Fall

Galileo's Assistant and the Case of the Variable *g*

You have just taken on a summer job as an assistant in a small private research lab in Pisa, Italy. Your boss, Galileo, has determined through a series of careful experiments that objects of different masses roll down an inclined plane at the same rate. He has further hypothesized, based on these experiments, that objects in free fall should always fall at the same rate, no matter what their masses are. This result contradicts the popular theory of the ancient Greek philosopher Aristotle (384–322 BCE), who believed that all falling objects travel downward at speeds directly proportional to their masses.

In one preliminary experiment, Galileo drops a wooden ball and a crumpled piece of parchment at the same time from near the ceiling of the lab. Instead of reaching the ground at the same time, the wooden ball lands shortly before the parchment does, apparently supporting Aristotle's theory. Galileo suspects that other factors are coming into play, such as air resistance. However, he also knows that opponents of his theory would claim that the two objects experience different free-fall accelerations because they have different masses.

Your assignment is to help Galileo by accurately measuring the free-fall acceleration, g, of several objects. If you find that all the objects fall with the same rate of acceleration, you will confirm Galileo's hypothesis. Short of that, you may disprove Aristotle's hypothesis if you find that a heavier object sometimes falls with the same acceleration as—or even with lesser acceleration than—a lighter object.

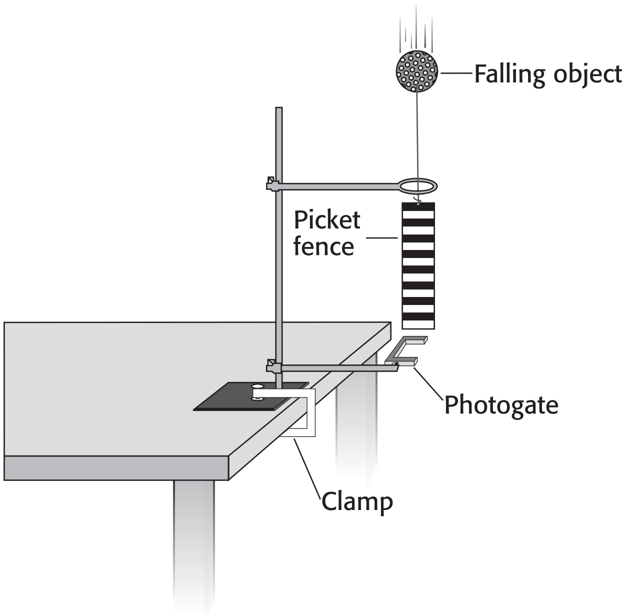

Figure 1

OBJECTIVES

Measure the acceleration of several falling objects of different masses.

Compare measured free-fall accelerations with an accepted standard value.

Determine whether or not the free-fall acceleration of an object depends directly on the object's mass.

MATERIALS LIST

- graphing calculator with link cable
- CBL 2™ or LabPro® system
- DataMate® application loaded in calculator
- Vernier photogate with CBL adapter
- Vernier picket fence
- table clamp and rod
- support ring with clamp
- additional clamp (for attaching photogate)
- string, 1 m long
- assorted objects: plastic ball, crumpled newspaper, baseball, balloon, etc.
- cushion, pillow, or padded catch box
- tape, strong, clear

SAFETY

- Perform this experiment in a clear area. Attach masses securely. Falling, dropped, or swinging masses can cause serious injury.
- Tie back long hair, secure loose clothing, and remove loose jewelry to keep them from getting caught in moving or rotating parts.

Developing the Model

Fortunately, you have access to rather sophisticated equipment to help Galileo. You will use a CBL® unit connected to a photogate and a graphing calculator. You will measure acceleration using a "picket fence," a transparent plastic sheet with evenly spaced black bars. As the picket fence falls through the photogate, the bars of the picket fence will interrupt the infrared beam between the arms of the photogate. The CBL will measure the time from the leading edge of one bar blocking the beam until the leading edge of the next bar blocks the beam. This timing continues as all eight bars pass through the photogate. From these measured times, the DataMate® application calculates the velocities for each of the intervals between the bars of the picket fence.

Answer the following questions before starting this activity.

1. The CBL unit measures the time interval between each black bar on the picket fence. What other information would you need to determine the average velocity between any two of the black bars?

____

____

____

2. If the picket fence is not vertical when it passes through the photogate, how might that affect your data?

____

____

____

3. Sketch a graph of velocity versus time for an object in free fall. What does the shape of the graph suggest about the acceleration of the object as it falls?

____

____

____

____

4. What are the units of the slope of a line on a of velocity-time graph? What physical quantity does this slope represent?

____

____

____

Procedure

PART I PICKET FENCE IN FREE FALL

1. Prepare a data table like the first one shown in the Data Tables section. Use a balance to measure the mass of the picket fence, and record the mass in your data table.

2. Securely anchor a table clamp and rod to the edge of a table. Fasten the photogate to the lower portion of the rod so the arms extend horizontally, as shown in **Figure 1.** Place a cushion or a catch box on the ground under the photogate to catch the picket fence after it falls.

3. Connect the photogate to the DIG/SONIC input on the CBL 2 or LabPro using the photogate adapter. Use the black link cable to connect the CBL unit to the calculator. Firmly press in the cable ends. Turn on the CBL unit and the calculator. Start the DataMate application from the APPS menu.

4. Set up the calculator and CBL for motion timing with the photogate.
- Select SETUP from the main screen.
- Select MOTION from the PHOTOGATE MODES screen.
- Select VERNIER PICKET FENCE from the SELECT DEVICE screen.
- Select OK from the SETTINGS screen.

5. Now you are prepared to collect free-fall data. To do this, select START from the main screen. Wait for the interface to beep.

6. Hold the picket fence in a vertical position just above the photogate, grasping it by the top edge. Drop the picket fence through the photogate, releasing it from your grasp completely before it crosses the infrared photogate beam. The picket fence must not touch the photogate as it falls, but the black bars must interrupt the infrared beam. The picket fence should remain vertical as it passes through the photogate.

7. Press ENTER to display a graph of distance versus time. Press ENTER again to return to the SELECT GRAPH menu. Select VELOCITY to display a graph of velocity versus time. Sketch this graph for later use. ***Proceed to step 1 of the Analysis section before continuing.***

8. To establish the reliability of your data, repeat steps 5-7 four more times. Use only drops in which the picket fence passes cleanly through the photogate and drops in which the photogate remains vertical. For each trial, record the slope values in your data table.

PART II OBJECTS OF DIFFERENT MASSES IN FREE FALL

9. Now you will find the free-fall accelerations of several objects, each of which is attached to the picket fence. The objects (plastic ball, crumpled paper, etc.) will all be about the same size and shape, to minimize the influence of factors such as air resistance. Securely clamp a small support ring to the rod, above the photogate, leaving at least 40 cm between the ring and the photogate. This ring will keep the objects you drop from hitting the photogate. Use a piece of strong, clear tape to securely attach a piece of string to the picket fence.

10. Use a balance to measure the combined mass of the picket fence, the string, and the first object you will be using. Record the mass in your data table. If you already know the other objects you will be using, you may want to measure their masses (combined with the picket fence and string) now.

11. Run one end of the string up through the support ring, and then securely tie or tape the other end of the string to the first object you will be using. Make sure the cushion or catch box is still directly under the picket fence and photogate.

12. Repeat steps 5–8 for a total of five trials, each time holding and releasing the object so that the picket fence falls through the photogate. Your lab partner may need to steady the picket fence to stop it from swinging before you release the object. ***After each trial, perform step 1 of the Analysis section and record the slope values in your data table.***

13. Repeat steps 10–12 three or four times with different objects attached to the picket fence. Record all slope values in your data table. ***When you are finished, proceed to step 2 of the Analysis section.***

DATA TABLES

Object	Mass (kg)	Slope (trial 1)	Slope (trial 2)	Slope (trial 3)	Slope (trial 4)	Slope (trial 5)
picket fence alone						
plastic ball, picket fence, and string						
crumpled paper, picket fence, and string						
baseball-sized balloon, picket fence, and string						
baseball, picket fence, and string						

Object	Average slope	Free-fall acceleration (m/s^2)	Percent uncertainty
picket fence alone			
plastic ball, picket fence, and string			
crumpled paper, picket fence, and string			
baseball-sized balloon, picket fence, and string			
baseball, picket fence, and string			

Analysis

1. **Curve Fitting** The slope of a velocity-time graph is a measure of acceleration. If the velocity graph is approximately a straight line of constant slope, the acceleration is constant. You may fit a straight line to your data in the following way:
   - Press ENTER, and select RETURN TO MAIN SCREEN from the SELECT GRAPH screen.
   - Select ANALYZE from the main screen.
   - Select CURVE FIT from the ANALYZE screen.
   - Select LINEAR (VELOCITY VS TIME) from the SELECT CURVE FIT screen.
   - Record the slope of the fitted line in your data table.
   - Press ENTER to see the fitted line superimposed on your velocity-time graph.
   - To return to the main screen, press ENTER, select RETURN TO ANALYZE screen, and then select RETURN TO MAIN SCREEN.

   If you have not yet completed the Procedure, return to step 9 in the Procedure now.

2. **Calculating Averages** Prepare a data table like the second one shown in the Data Tables section. For each object, including the picket fence alone, use the slope values for all five trials to calculate the average slope value for that object. Record the average slopes in your new data table. These averages are the rates of free-fall acceleration for each object. Note, however, that the DataMate application treats all velocities as positive, so the slopes are also positive. The free-fall acceleration, however, is negative, because the downward direction is negative by convention.

3. Calculating Uncertainty For each object, the minimum and maximum values among the trials give an indication of *uncertainty*, or how much the measurements can vary from trial to trial. Choose the lowest value and the highest value from several trials, and find the difference between them. Divide this value in half to find the uncertainty. Round the uncertainty to one digit, and round the average value from item 2 to the same decimal place. Calculate uncertainty in this way for each object. Record your final answers as $-average \pm uncertainty$ under the heading *Free-fall acceleration* in your data table (the initial minus sign indicates that the acceleration is downward).

4. Calculating Percent Uncertainty Uncertainty is often expressed as a percentage. Calculate the percent uncertainty of your free-fall acceleration for each object using the following equation, and record your results in your data table.

$$percent\ uncertainty = \frac{uncertainty}{average} \times 100\%$$

Conclusions

5. Determining Accuracy Compare your value of the free-fall acceleration for the picket fence alone to the generally accepted value of *g*, 9.81 m/s^2. Does the accepted value fall within the range of your values?

____

____

____

____

6. **Comparing Values** Which objects have a free-fall acceleration closest to the free-fall acceleration of the picket fence alone? Which objects have free-fall accelerations that are farthest from the free-fall acceleration of the picket fence alone?

7. **Interpreting Results** For the object with the free-fall acceleration farthest from that for the picket fence alone, does the free-fall acceleration, including uncertainty, lie completely outside the value of free-fall acceleration for the picket fence alone, including uncertainty? Does this support or contradict Galileo's hypothesis that free-fall acceleration is independent of mass?

8. **Making Predictions** If Galileo dropped a baseball and a baseball-sized balloon from the Leaning Tower of Pisa, would he be able to demonstrate that all objects experience the same free-fall acceleration? Explain.

9. **Formulating Hypotheses** If all the objects you tested did not fall with the same rate of acceleration, propose an explanation of the variations in your measured values of free-fall acceleration that you or Galileo could offer to critics of Galileo's hypothesis.

10. Interpreting Results Do your results show, for any two objects, a heavier object accelerating at the same rate as a lighter object, or even accelerating at a slower rate than a lighter object? Does this support or contradict Aristotle's hypothesis that free-fall acceleration is directly proportional to mass?

____

____

____

____

____

Extensions

1. **Graphing** Plot a graph of free-fall acceleration versus mass for the various objects you tested. Above and below each data point, draw short lines that span the length of the uncertainty on either side of the average acceleration values. Try to find a line that intersects all of the data points. Does your result support or contradict Aristotle's hypothesis that free-fall acceleration is directly proportional to mass?

2. **Curve Fitting** Galileo's study of free-fall acceleration led, among other things, to the following quadratic equation for displacement with constant acceleration:

$$\Delta x = v_i \Delta t + \frac{1}{2} a (\Delta t)^2$$

Run the experiment again with the picket fence alone, and this time display a graph of distance versus time. Perform step 1 of the Analysis section again, but this time select QUADRATIC (VELOCITY VS TIME) from the SELECT CURVE FIT screen. Sketch the resulting graph and fitted curve. What geometric shape is the fitted curve?

3. **Extending Research** Research how the value of free-fall acceleration, *g*, varies at different locations around the world. For example, how does altitude affect the value of *g*? How much can g vary at a location in the mountains compared to a location at sea level? What other factors may cause free-fall acceleration to vary at different locations?