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Measuring *g* Three Ways

Experiments:

Picket Fence Free Fall

- Go Direct Photogate

Ball Toss

- Go Direct Motion

Free Fall (no handout)

- Vernier Video Analysis

Workshop presenters:
Fran Poodry
Tom Smith
physics@vernier.com

Vernier Software & Technology • 888-VERNIER (888-837-6437)
info@vernier.com • www.vernier.com

Picket Fence Free Fall

We say an object is in *free fall* when the only force acting on it is the Earth's gravitational force. No other forces can be acting; in particular, air resistance must be either absent or so small as to be ignored. When the object in free fall is near the surface of the Earth, the gravitational force on it is essentially constant. As a result, an object in free fall accelerates downward at a constant rate. This acceleration is usually represented with the symbol, *g*.

Physics students measure the acceleration due to gravity using a wide variety of timing methods. In this experiment, you will have the advantage of using a very precise timer and a photogate. The photogate has a beam of infrared light that travels from one side to the other. It can detect whenever this beam is blocked. You will drop a piece of clear plastic with evenly spaced black bars on it, called a Picket Fence. As the Picket Fence passes through the photogate, the photogate measures 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 software calculates and plots the velocities and accelerations for this motion.

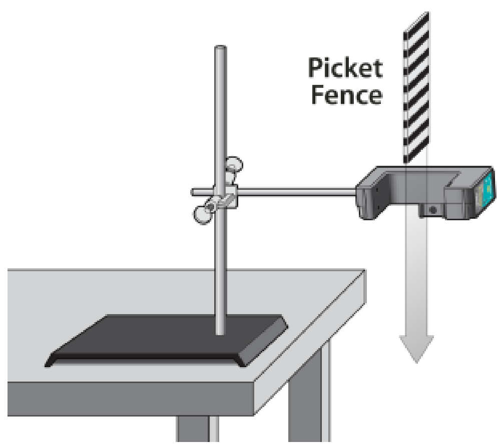

Figure 1

OBJECTIVE

Measure the acceleration of a freely falling body, *g*, to better than 0.5% precision using a Picket Fence and a Photogate.

MATERIALS

- Chromebook, computer, **or** mobile device
- Graphical Analysis app
- Go Direct Photogate
- Picket Fence
- clamp and ring stand to secure Photogate

PRELIMINARY QUESTIONS

1. Inspect your Picket Fence. You will be dropping it through a photogate to measure *g*. The distance, measured from one edge of a black band to the same edge of the next band, is 5.0 cm. What additional information is needed to determine the average speed of the Picket Fence as it moves through the photogate?

2. If an object is moving with constant acceleration, what is the shape of its velocity *vs.* time graph?

3. Does the initial velocity of an object have anything to do with its acceleration? For example, compared to dropping an object, if you throw it downward would the acceleration be different after you released it?

PROCEDURE

1. Fasten the Photogate rigidly to a ring stand so the arms extend horizontally, as shown in Figure 1. The entire length of the Picket Fence must be able to fall freely through the Photogate. To avoid damaging the Picket Fence, provide a soft landing surface (such as a carpet).

2. Set up the Photogate.

   a. Launch Graphical Analysis.

   b. Connect the Photogate to your computer, Chromebook, or mobile device.

   c. Click or tap Sensor Channels.

   d. Enable the Gate 1 - Gate State channel and disable the Object Velocity channel.

   e. Click or tap Done.

3. Click or tap View, ⊞, and choose 2 Graphs. If the second graph is not a graph of velocity *vs*. time, click or tap the y-axis label on the second graph and select Velocity. Dismiss the box to view the graph.

4. Observe the live Gate State readings in Graphical Analysis. Block the Photogate with your hand; note that the Gate State changes to **1**, indicating the gate is blocked. Remove your hand and the display should change to **0** (unblocked).

5. Click or tap Collect to start data collection. **Note**: Data will be displayed on the graph when the gate is blocked for the first time after data collection is started.

6. Hold the top of the Picket Fence between two fingers, allowing the Picket Fence to hang freely just above the center of the Photogate, without blocking the gate. Release the Picket Fence so it leaves your grasp completely before it enters the Photogate. The Picket Fence must remain vertical and should not touch the Photogate as it falls.

7. When the Picket Fence has completely passed through the Photogate, a graph of position *vs.* time and velocity *vs.* time appears on the screen. Sketch the graphs on paper for later use.

8. Examine your velocity *vs.* time graph. The slope of a velocity *vs.* time graph is a measure of acceleration. If the velocity graph is approximately a straight line of constant slope, the acceleration is constant. If the acceleration of your Picket Fence appears constant, fit a straight line to your data.

    a. Click or tap Graph Tools, , and choose Apply Curve Fit.
    b. Select Linear as the curve fit. Click or tap Apply.
    c. Record the slope of the linear curve fit in the data table.
    d. Dismiss the Linear curve fit box.

9. To establish the reliability of your slope measurement, repeat Steps 5–8 five more times. Do not use drops in which the Picket Fence hits or misses the Photogate. Record the slope values in the data table.

DATA TABLE

Trial	1	2	3	4	5	6
Slope (m/s^2)						

	Minimum	Maximum	Average
Acceleration (m/s^2)			

Acceleration due to gravity, *g*	±	m/s^2
Precision		%

ANALYSIS

1. From your six trials, determine the minimum, maximum, and average values for the acceleration of the Picket Fence. Record them in the data table.

2. Describe in words the shape of the position *vs.* time graph for the free fall.

3. Describe in words the shape of the velocity *vs.* time graph. How is this related to the shape of the position *vs.* time graph?

4. The average acceleration you determined represents a single best value, derived from all your measurements. The minimum and maximum values give an indication of how much the measurements can vary from trial to trial; that is, they indicate the precision of your measurement. One way of stating the precision is to take half of the difference between the minimum and maximum values and use the result as the uncertainty of the measurement.

Express your final experimental result as the average value, ± the uncertainty. Round the uncertainty to just one digit and round the average value to the same decimal place.

For example, if your minimum, average, and maximum values are 9.12, 9.93, and 10.84 m/s^2, express your result as g = 9.9 ± 0.9 m/s^2. Record your values in the data table.

5. Express the uncertainty as a percentage of the acceleration. This is the precision of your experiment. Enter the value in your data table. Using the example numbers from the last step, the precision would be

$$\frac{0.9}{9.9} \times 100\% = 9\%$$

6. Compare your measurement to the generally accepted value of *g* (from a textbook or other source). Does the accepted value fall within the range of your values? If so, your experiment agrees with the accepted value.

7. Inspect your velocity graph. How would the associated acceleration *vs.* time graph look? Sketch your prediction on paper. Change the y-axis to acceleration. Comment on any differences between the acceleration graph and your prediction. To examine the data pairs on the displayed graph, tap any data point. As you tap each data point, the acceleration and time values are displayed. Note that the vertical scale of the graph does not include zero. Is the variation as large as it appears?

8. Use the Statistics tool and the acceleration graph to find the average acceleration. How does this compare with the acceleration value for the same drop, determined from the slope of the velocity graph?

EXTENSIONS

1. Use the position *vs.* time data and a quadratic fit to determine *g*.

2. Would dropping the Picket Fence from higher above the Photogate change any of the parameters you measured? Try it.

3. Would throwing the Picket Fence downward, but letting go before it enters the Photogate, change any of your measurements? How about throwing the Picket Fence upward? Try performing these experiments.

4. How would adding air resistance change the results? Try adding a loop of clear tape to the upper end of the Picket Fence. Drop the modified Picket Fence through the Photogate and compare the results with your original free-fall results.

5. Investigate how the value of *g* varies around the world. For example, how does latitude affect the value of *g*? What other factors cause this acceleration to vary at different locations? For example, is *g* different at high latitudes such as Svalbard, an archipelago north of Norway?

6. Collect *g* measurements for your entire class, and plot the values in a histogram. Is there a most common value? Are the measurements consistent with one another?

Ball Toss

When a juggler tosses a ball straight upward, the ball slows down until it reaches the top of its path. The ball then speeds up on its way back down. A graph of its velocity *vs.* time would show these changes. Is there a mathematical pattern to the changes in velocity? What is the accompanying pattern to the position *vs.* time graph? What would the acceleration *vs.* time graph look like?

In this experiment, you will use a motion detector to collect position, velocity, and acceleration data for a ball thrown straight upward. Analysis of the graphs of this motion will answer the questions asked above.

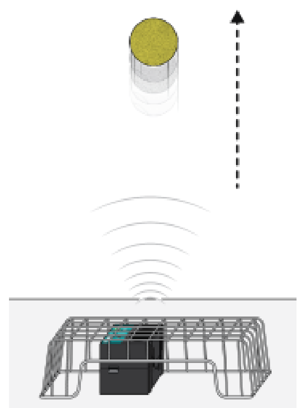

Figure 1

OBJECTIVES

- Collect position, velocity, and acceleration data as a ball travels straight up and down.
- Analyze position *vs.* time, velocity *vs.* time, and acceleration *vs.* time graphs.
- Determine the best-fit equations for the position *vs.* time and velocity *vs.* time graphs.
- Determine the mean acceleration from the acceleration *vs.* time graph.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Motion
volleyball **or** basketball
wire basket

PRELIMINARY QUESTIONS

1. Consider the motion of a ball as it travels straight up and down in freefall. Sketch your prediction for the position *vs.* time graph. Describe in words what this graph means.

2. Sketch your prediction for the velocity *vs.* time graph. Describe in words what this graph means.

3. Sketch your prediction for the acceleration *vs.* time graph. Describe in words what this graph means.

PROCEDURE

1. Launch Graphical Analysis. Connect the motion detector to your Chromebook, computer, or mobile device.

2. Place the motion detector on the floor and protect it by placing a wire basket over it.

3. Collect data. During data collection you will toss the ball straight upward above the motion detector and let it fall back toward the motion detector. It may require some practice to collect clean data. To achieve the best results, keep in mind the following tips:

   - Hold the ball approximately 0.5 m directly above the motion detector when you start data collection.
   - A toss so the ball moves from 0.5 m to 1.0 m above the motion detector works well.
   - After the toss, catch the ball at a height of 0.5 m above the motion detector and hold it still until data collection is complete.
   - Use two hands and pull your hands away from the ball after it starts moving so they are not picked up by the motion detector.

   When you are ready to collect data, click or tap Collect to start data collection and then toss the ball as you have practiced.

DATA TABLE

Curve fit parameters	A	B	C
Position ($Ax^2 + Bx + C$)			
Velocity ($Ax + B$)			
Average acceleration			

ANALYSIS

1. Export, print, or sketch the three motion graphs. To display an acceleration *vs.* time graph, change the y-axis of the velocity graph to Acceleration. The graphs you have recorded are fairly complex and it is important to identify different regions of each graph. Record your answers directly on your copy of the graphs.

   a. Identify the region when the ball was being tossed but was still in your hands.

      - Examine the velocity *vs.* time graph and identify this region. Label this on the graph.
      - Examine the acceleration *vs.* time graph and identify the same region. Label this on the graph.

   b. Identify the region where the ball is in free fall.

      - Label the region on each graph where the ball was in free fall and moving upward.
      - Label the region on each graph where the ball was in free fall and moving downward.

   c. Determine the position, velocity, and acceleration at these specific points.

      - On the velocity *vs.* time graph, locate where the ball had its maximum velocity, after the ball was released. Mark the spot and record the value on the graph.
      - On the position *vs.* time graph, locate the maximum height of the ball during free fall. Mark the spot and record the value on the graph.
      - What was the velocity of the ball at the top of its motion?
      - What was the acceleration of the ball at the top of its motion?

2. The motion of an object in free fall is modeled by $y = \frac{1}{2} gt^2 + v_0t + y_0$ where y is the vertical position, g is the magnitude of the free-fall acceleration, t is time, and v_0 is the initial velocity. This is a quadratic equation whose graph is a parabola.

   Examine the position *vs.* time graph to see if it is a parabola in the region where the ball was in freefall. If it is, fit a quadratic equation to your data.

   a. Select the data in the region that corresponds to when the ball was in freefall.
   b. Click or tap Graph Tools, , for the position *vs*. time graph and choose Apply Curve Fit.
   c. Select Quadratic as the curve fit and click or tap Apply.
   d. Record the parameters of the curve fit in the data table.

3. How closely does the coefficient of the x^2 term in the curve fit compare to $\frac{1}{2}$ g?

4. What does a linear segment of a velocity *vs.* time graph indicate? What is the significance of the slope of that linear segment?

5. Display a graph of velocity *vs.* time. This graph should be linear in the region where the ball was in freefall. Fit a linear equation to your data in this region.

   a. Select the data in the region that corresponds to when the ball was in freefall.
   b. Click or tap Graph Tools, , for the velocity *vs*. time graph and choose Apply Curve Fit.
   c. Select Linear as the curve fit and click or tap Apply.
   d. Record the parameters of the curve fit in the data table.

6. How closely does the coefficient of the *x* term compare to the accepted value of *g*?

7. Examine the graph of acceleration *vs.* time. During free fall, the acceleration graph should appear to be more or less constant. Note that because the graph is automatically scaled to fill the screen vertically, small variations may appear large. A good way to analyze the acceleration data is to find the mean (average) of these data points.

   a. Click or tap Graph Tools, , and choose View Statistics.

   b. Record the mean acceleration value in your data table.

8. How closely does the mean acceleration value compare to the values of *g* found in Steps 3 and 6?

9. List some reasons why your values for the ball's acceleration may be different from the accepted value for *g*.

EXTENSIONS

1. Determine the consistency of your acceleration values and compare your measurement of *g* to the accepted value of *g*. Do this by repeating the ball toss experiment five more times. Each time, fit a straight line to the free-fall portion of the velocity graph and record the slope of that line. Average your six slopes to find a final value for your measurement of *g*. Does the variation in your six measurements explain any discrepancy between your average value and the accepted value of *g*?

2. The ball used in this lab is large enough and light enough that a buoyant force and air resistance may affect the acceleration. Perform the same curve fitting and statistical analysis techniques, but this time analyze each half of the motion separately. How do the fitted curves for the upward motion compare to the downward motion? Explain any differences.

3. Perform the same lab using a beach ball or other very light, large ball.

4. Use a smaller, more dense ball where buoyant force and air resistance will not be a factor. Compare the results to your results with the larger, less dense ball.

5. Instead of throwing a ball upward, drop a ball and have it bounce on the ground. (Position the motion detector above the ball.) Predict what the three graphs will look like, then analyze the resulting graphs using the same techniques as this lab.