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Capturing Motion: Hands-On Physics Learning with Vernier Photogates

Experiments

Picket Fence Free Fall

- Go Direct Photogate

Atwood's Machine

- Go Direct Photogate with Ultra Pulley Attachment

Hang Time

- Go Direct Photogate

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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.

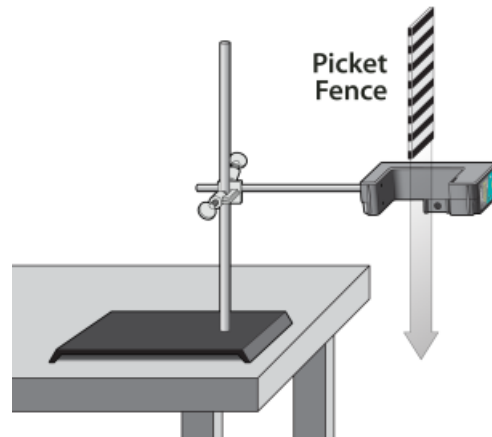


Figure 1

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, <i>g</i>	±	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.

Picket Fence Free Fall

Express your final experimental result as the average value, \pm 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/s², express your result as $g = 9.9 \pm 0.9$ m/s². Record your values in the data table.

- 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

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

- 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.
- 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?
- 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

- Use the position vs. time data and a quadratic fit to determine g .
- Would dropping the Picket Fence from higher above the Photogate change any of the parameters you measured? Try it.
- 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.
- 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.
- 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?
- 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?

Atwood's Machine

A classic experiment in physics is the *Atwood's machine*: two masses on either side of a pulley connected by a light string. When released, the heavier mass accelerates downward while the lighter one accelerates upward at the same rate. The acceleration depends on the difference in the two masses, as well as the total mass.

In this experiment, you will determine the relationship between the two factors that influence the acceleration of an Atwood's machine using a Photogate to record the machine's motion.

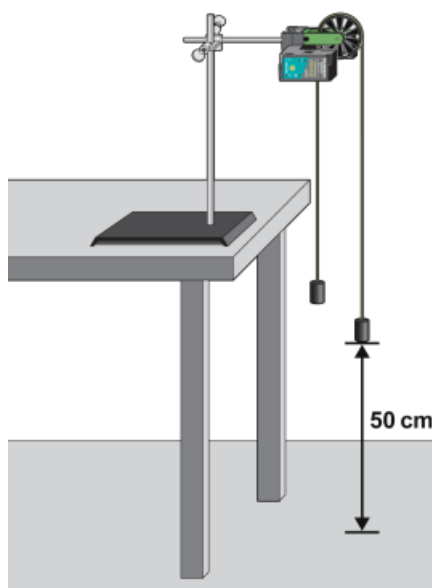


Figure 1

OBJECTIVES

- Use a Photogate to study the acceleration of an Atwood's machine.
- Determine the relationships between the masses on an Atwood's machine and the acceleration.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Photogate with Ultra Pulley Attachment
ring stand
right-angle clamp
mass set
string, 1.2 m long
graph paper (optional)

PRELIMINARY QUESTIONS

1. If two objects of equal mass are suspended from either end of a string passing over a light pulley, as in Figure 1, what kind of motion do you expect to occur? Why?
2. Draw a free-body diagram of the left-side mass in Figure 1. Draw another of the right-side mass. Include all forces acting on each mass.
3. Do the two masses have the same acceleration? Why?
4. How would you expect the acceleration of an Atwood's machine to change if you
 - Increase the mass on one side and decrease the mass on the other, keeping the total mass constant?
 - Gradually increase the mass of both sides, keeping the difference in mass constant?

PROCEDURE

Part I Constant Total Mass

For this part of the experiment you will keep the total mass used constant, but move weights from one side to the other. The difference in masses changes.

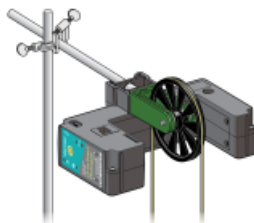




Figure 2

1. Set up the Atwood's machine apparatus as shown in Figures 1 and 2. **Note:** The masses must be able to move at least 40 cm before the heavier mass strikes the floor.
2. Launch Graphical Analysis. Connect the Photogate with Ultra Pulley to your computer, Chromebook, or mobile device. Click or tap Sensor Channels, and select Gate 2 - Gate State only.
3. Set up Graphical Analysis for a pulley with a string that runs in a groove.
 - a. Click or tap Mode. Graphical Analysis is set to Photogate Timing, Linear Motion mode.
 - b. Change the Object to Ultra Pulley - in groove.
 - c. Click or tap Done.
4. Arrange a collection of masses totaling 100 g on m_2 and a 100 g mass on m_1 . What is the acceleration of this combination? Record your values for mass and acceleration in the data table.
5. Move 5 g from m_2 to m_1 . Record the new masses in the data table.

6. To measure the acceleration of this system, start with the masses even with each other. Steady the masses so they are not swinging. Click or tap Collect to start data collection. After a moment, release the smaller mass, catching the falling mass before it strikes the floor or the other mass strikes the pulley. Click or tap Stop to stop data collection.
7. Click or tap View, , and choose 1 Graph. If necessary, change the y-axis to display a graph of velocity vs. time. Examine the graph. The slope represents the acceleration of the masses.
8. Fit a straight line to the velocity vs. time graph.
 - a. Click or tap Graph Tools, , and choose Apply Curve Fit.
 - b. Select Linear as the curve fit.
 - c. Record the slope of the linear curve fit (acceleration) in the data table and then dismiss the Linear curve fit box.
9. Continue to move masses from m_2 to m_1 in 5 g increments, changing the difference between the masses, but keeping the total constant. Repeat Steps 6–8 for each mass combination. Continue until you collect data for at least five different mass combinations.

Part II Constant Mass Difference

For this part of the experiment you will keep the difference in mass between the two sides of the Atwood's machine constant and increase the total mass.

10. Use 50 g for m_1 and 60 g for m_2 .
11. Repeat Steps 6–8 to collect data and determine the acceleration.
12. Add mass in 10 g increments to both sides, keeping a constant difference of 10 grams. Record the resulting mass for each combination in the data table. Collect motion data and determine the acceleration for at least five different mass combinations.

DATA TABLE

Part I Constant Total Mass

Trial	m_1 (kg)	m_2 (kg)	Acceleration (m/s ²)	$m_{\text{diff}},$ $m_1 - m_2$ (kg)	m_T (kg)
1					
2					
3					
4					
5					

Part II Constant Mass Difference

Trial	m_1 (kg)	m_2 (kg)	Acceleration (m/s ²)	$m_{\text{diff}},$ $m_1 - m_2$ (kg)	m_T (kg)
1					
2					
3					
4					
5					

ANALYSIS

1. For each trial, calculate the difference between m_1 and m_2 . Enter the result in the column labeled m_{diff} .
2. For each trial, calculate the total mass in grams. Enter the result in the column labeled m_T .

3. Plot a graph of acceleration vs. m_{diff} , using the Part I data. Based on your analysis of the graph, what is the relationship between the mass difference and the acceleration of an Atwood's machine?
4. Similarly, plot a graph of acceleration vs. m_{T} , using the Part II data. Based on your analysis, what is the relationship between total mass and the acceleration of an Atwood's machine?
5. Develop a single expression for the acceleration of an Atwood's machine, combining the results of the previous two steps in the analysis.

EXTENSIONS

1. Draw a free body diagram of m_1 and another free body diagram of m_2 . Using these diagrams, apply Newton's second law to each mass. Assume that the tension is the same on each mass and that they have the same acceleration. From these two equations, find an expression for the acceleration of m_1 in terms of m_1 , m_2 , and g . Compare the expression to your result in Step 5 of Analysis.
2. For each of the experimental runs you made, calculate the expected acceleration using the expression you found with Newton's second law of motion and the specific masses used. Compare these figures with your experimental results. Are the experimental acceleration values low or high? Why?
3. An unknown mass can be placed on one side of the Atwood's machine. Using lab measurements and any necessary calculations, the mass of the unknown can be determined. Try it.
4. How does the force exerted upward by the pulley change as the system begins accelerating? Why? Set up an experiment to determine how this force changes.
5. How does the tension in the string change as the masses start to move? Or does it?

Hang Time

We are all impressed by athletes with a long hang time, especially in sports such as basketball. The player most famous for hang time is probably Michael Jordan, with a hang time of 0.92 seconds.

In this activity, you will measure your hang time and use it to determine your jump height. We'll look at values for the group.

OBJECTIVES

- Measure hang time using a laser and photogate
- Calculate jump height
- Compare hang times and jump heights

MATERIALS

Graphical Analysis App

Go Direct Photogate

Laser pointer

Tape

PROCEDURE

Caution: Even though we are using a class 2 laser, it is never a good idea to shine a laser beam into your eyeball. Do not look into the laser beam.

1. Set up the photogate and laser pointer on the floor, such that the laser pointer is aimed into the laser opening on the photogate and there is enough room between the photogate and laser pointer for a person to stand and jump. You may need to find a way to keep the laser pointer turned on. You may need tape.
2. Launch Graphical Analysis and connect the photogate.
3. In the Sensor Channels menu, enable Laser Gate - Gate State and disable all other channels.
4. Change the mode to Timer or Period
 - a. Click or tap Mode
 - b. Change Measurement to Timer or Period
 - c. Select Time between gates
 - d. Click or tap Done
5. Confirm that the laser is aligned correctly with the hole on the photogate. The blue LED marked L will turn off when the laser is correctly aligned, and the meter on Graphical Analysis will indicate Laser Gate State: 0.
6. Get ready, get set, jump
 - a. The person jumping should stand between the laser beam and the photogate, blocking the beam.

- b. Click or tap Collect.
 - c. Jump and land back in the same spot, briefly unblocking the laser beam and blocking it again.
 - d. Click or tap Stop.
7. Record the data
 - a. The time begins when the laser beam is unblocked and ends when it is blocked. This is the hang time.
 - b. Record this value.
8. Repeat steps 6–7 for several people or multiple times, to get a range of values. Record all the values.

ANALYSIS

1. Use the kinematic expression for position as a function of time under a constant acceleration to derive an expression for the distance from the maximum height of the jump to landing on the floor as a function of time.
2. Since the time from the top of the jump to landing on the floor is half the total hang time, divide all the collected hang time data in half.

Hint: You can do this in Graphical Analysis by using a calculated column.
3. Calculate the maximum height for each jump based on the half hang time number.

Hint: This is also quickly done using a calculated column.
4. Since your maximum height is in meters, convert to inches.

Hint: There are 38.37 inches in 1 meter.
5. Do you notice any patterns when you look at the aggregated hang time or jump height data?
6. Michael Jordan famously had a hang time of 0.92 seconds. What maximum jump height does this correspond to, in meters and also in inches?
7. The Guinness world record for standing jump (for a male human) is 1.70 m (5 ft 7 in), and was achieved by Christopher Spell (USA) in Shrub Oak, New York, USA, on 7 February 2021.

While this is the jump height for Mr. Spell's feet, his center of mass did not achieve the same change in height. However, if his center of mass DID change by 1.70 m, what would Mr. Spell's maximum hang time be?