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## Experiment A1 Galileo's Inclined Plane Procedure

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**Deliverables:** Checked lab notebook, brief Tech Memo

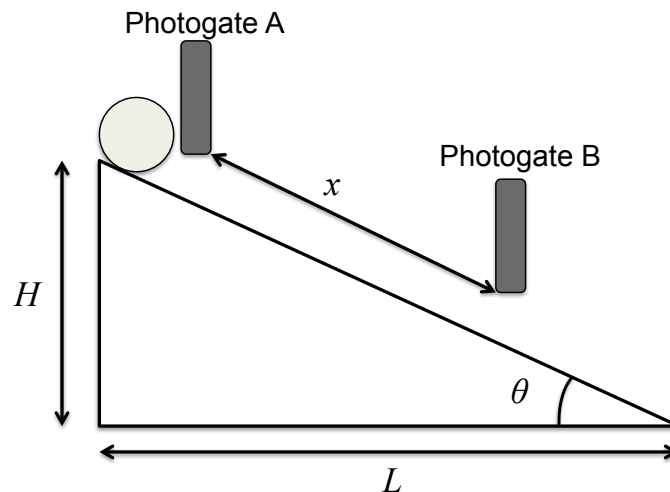
**Recommended Reading:** Section 1.3, Section 10.3, and Example 17.1 of the textbook

### Overview

In this lab, you will perform Galileo's famous inclined plane experiment. You will then learn several fundamental techniques to analyze the data. Specifically, you will *empirically* demonstrate a mathematical relationship for distance  $x$  vs. time  $t$  for a body in gravitational free-fall and extrapolate the acceleration of gravity  $g$ . This experiment is of great historical significance, as it later inspired Isaac Newton to invent calculus.

### Part I: Galileo's Inclined Plane

In this experiment, you will roll a ball down an inclined plane and measure the time  $t$  it takes to travel a distance  $x$ .



**Figure 1** – A schematic representing the inclined plane experiment.

According to Newtonian Mechanics, the trajectory of a sphere rolling down an inclined plane at an angle  $\theta$  is given by

$$x(t) = \frac{1}{2} \left( \frac{5}{7} g \sin \theta \right) t^2 + v_0 t + x_0 \quad (1)$$

where  $g$  is the acceleration of gravity near the surface of earth,  $v_0$  is the initial velocity, and  $x_0$  is the initial position.

*Procedure:*

1. Determine the angle by measuring the length of the legs  $L$  and  $H$  and using the appropriate trig function. Record all values in your lab notebook.
2. Use the lab stand to position Photogate A near the top of the inclined plane as shown in Fig. 1 and connect it to the LabQuest via Digital Port 1 (DIG 1). Adjust the photogate height such that the ball will pass through the optical beam.
3. Use the other lab stand to position photogate B a distance  $x = 10$  cm away from photogate A, and connect it to the LabQuest via Digital Port 2 (DIG 2). Adjust the photogate height such that the optical beam will strike the center of the rolling ball.
4. Plug the LabQuest in and then turn it on.
5. In the “LabQuest App”, **File > New** on the drop down menu.
6. On the Sensors tab, select **Sensor > Sensor Setup**. Under “DIG 1” select the “Photogate” from the drop down box and then hit OK. Repeat this for “DIG 2”.
7. Again on the Sensors tab, select **Sensor > Data Collection** and choose the following parameters:  
**Mode: Photogate timing**  
**Photogate mode: Pulse**  
**Distance between gates: 0.02m (It doesn't really matter what you put here.)**  
**End data collection: check “with the stop button”**  
Under the “Pulse” mode, blocking Photogate A will start a timer in the LabQuest and blocking Photogate B will stop the timer. Exit the menu by pressing the “Ok” button.
8. Press the “▶” button to begin collecting data from the photogates. (Choose to discard any unsaved data if it asks.)
9. Make a table in your lab notebook with two columns for  $x$  and  $t$ . Be sure to note the units of both.
10. Measure the distance  $x$  between the two photogates using the meter stick provided and record it in the table in your notebook.
11. Make sure the heights of the photogate are set so that the light sensor will pass through the center of the ball.
12. Place the ball **directly behind Photogate A** and release it. Locate the “**Pulse Time**” in the upper right corner of the LabQuest. Record it in the table in your lab notebook.

**Pro-tip: Try to get the ball as close as possible to Photogate A before you release it.** There is a little red light that will turn on when you trip the photogate. If you accidentally trip Photogate A, you can reset the clock by tripping photogate B with your hand.

13. Without moving the photogates, repeat steps 9 – 12 four more times. This will give you a total of 5 data points each distance  $x$  that you will average together.
14. Increase  $x$  and repeat: Reposition Photogate B 10 cm further from A and repeat steps 7 – 13 for distances up to and including  $x = 50$  cm.
15. Have the lab TA sign your notebook before you leave!

## Data Analysis and Deliverables

Create the tables, schematics, plots, and other deliverables listed below. Save the plots as PDF or EPS files, import them into either Microsoft Word or LaTeX, and add an intelligent, concise caption. Additionally, write 1 – 3 paragraphs describing the items below. Any theoretical formula you used in your analysis should be included as a numbered equation within these paragraphs.

You must include the following items in your lab report:

1. Equation of motion,  $x$  vs. time  $t$ , for a ball rolling down an inclined plane.
2. The angle  $\theta$  you measured for your inclined plane.
3. A plot of distance  $x$  vs. time  $t$  for the inclined plane *with a quadratic curve fit*. (Plot the average of the 5 measured times.)
4. Extrapolated value of  $g$  with uncertainty (this should go in the caption of previous item)

### Instructions for Extrapolating $g$

- a) Using your data from Part I, make a plot of distance  $x$  as a function of *average* measured time  $t$ . (Distance  $x$  is on the vertical axis. Average time  $t$  is on the horizontal axis.) Please include the  $x = 0, t = 0$  data point.
- b) Using the “fit()” command in Matlab, perform a *quadratic* curve fit of your measured data.
- c) Plot the quadratic curve fit on top of your data.
- d) Based on Eq. (1), write an **algebraic** equation for each of the three fitting parameters in the quadratic equation. (“Algebraic” means leave the parameters as symbolic variables.)
- e) Use the coefficient for the second order term (the constant in front of  $t^2$  term) that you get from the curve fit to *extrapolate*  $g$ .
- f) The fit command also outputs a “95% confidence interval” for each fitting parameter. The width of this interval is equal to twice the uncertainty in the parameter. Use the confidence interval for the second order coefficient to determine the uncertainty in  $g$ .
- g) Report extrapolated value of  $g$  in the caption of the plot along with its uncertainty. Report it as  $g = \text{value} \pm \text{uncertainty m/s}^2$ . Round the “uncertainty” to two significant digits, and round the “value” to the least significant digit of the uncertainty.

**Talking Points** – Please discuss the following in your lab report.

- Explain how you determined the angle  $\theta$ .
- Compare your extrapolated value of  $g$  with the widely accepted value of  $9.81 \text{ m/s}^2$ . Is the accepted value within your error bars? What physical effects might cause them to be different?
- You used only one of the three fitting coefficients to extrapolate  $g$ . Now, consider the other two fitting coefficients. What do they physically represent? Do the values seem reasonable?

## Appendix A

### Equipment

#### Part I

- Inclined plane made from 80-20 rail
- Metal ball
- Meter stick
- Vernier LabQuest
- 2 lab stands
- 2 Photogates (Vernier VPG-BTD) with aluminum mounting rods
- 2 Photogate “DIG” cables