Free fall: Aristotle versus Galileo

Laboratory 11

Astronomy 120. The Copernican Revolution

Name	Full	Partial	None

1 How Do Things Fall?

The Ancient Greek philosopher Aristotle (384-322 BC) had a theory of motion that came to dominate Western thought for many centuries. In the 17th Century the Italian mathematician and natural philosopher Galileo Galilei (1564-1642 AD) challenged Aristotle's theory of motion and presented new ideas about how objects move. These two men proposed different models of how objects fall. We will investigate these two theories today.

Neither Aristotle nor Galileo directly tested their models, because it was too hard to do given the technology they had available. Aristotle's model was based mostly on watching objects fall. Galileo's model was based on experiments with balls rolling down inclined planes. In this lab we will test these two models directly by experimenting with a falling metal ball, in hopes of determining which one provides a better description of how objects near Earth's surface fall. [1]

2 Aristotle's Model and Galileo's Model

Note: in all cases discussed in this lab we are assuming that objects are being released from rest.

Aristotle thought that a heavy object would fall to earth with a constant speed. The speed at which the object would fall depended on how heavy the object was, with heavier objects falling faster. The idea that objects fall at constant speed provides a specific mathematical model for the motion of falling objects. If an object moves at constant speed the distance d it travels is related to the elapsed time t by the following equation:

$$d = vt,$$

where v is the speed at which the object falls. For now we will refer to this as *Aristotle's Model of Falling.*

Galileo thought that objects would fall in a different way. He thought that two objects released from the same height would fall together and that they would fall with the same constant *acceleration* as long as air resistance was negligible. This idea also provides us with a specific mathematical model for falling, although the model is different from Aristotle's. In Galileo's model the distance d is related to the time t by the equation

$$d = \frac{1}{2}at^2,$$

where a is the acceleration experienced by the falling object. For now we will refer to this as *Galileo's Model of Falling.*

[1] The first such direct test of these models was performed by the Jesuit astronomer Giovanni Battista Riccioli in Bologna, Italy and published in 1651. Riccioli was an opponent of Galileo who believed that the Earth was at rest at the center of the universe. If you are interested in Riccioli's results, see Graney, *Physics Today* (September 2012) pp. 36-40. Copies of this article are available *after* you have completed the experiment.

1. In Aristotle's Model the distance the object falls is ______________.

   (a) directly proportional to the elapsed time
   (b) inversely proportional to the elapsed time
   (c) directly proportional to the square of the elapsed time
   (d) inversely proportional to the square of the elapsed time

2. According to Aristotle's model, if an object falls 3 meters in 2 seconds, then it will fall ______________ in 4 seconds.

   (a) 4 m
   (b) 5 m
   (c) 6 m
   (d) 7 m

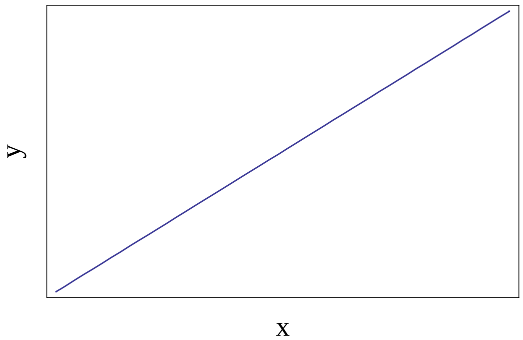
3. In Galileo's Model the distance the object falls is ______________.

   (a) directly proportional to the elapsed time
   (b) inversely proportional to the elapsed time
   (c) directly proportional to the square of the elapsed time
   (d) inversely proportional to the square of the elapsed time

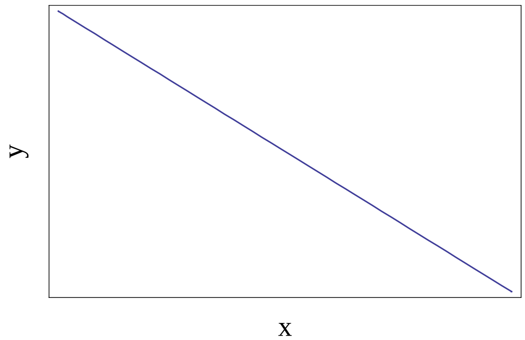
4. According to Galileo's model, if an object falls 3 meters in 2 seconds, then it will fall ______________ in 4 seconds.

   (a) 6 m
   (b) 8 m
   (c) 10 m
   (d) 12 m

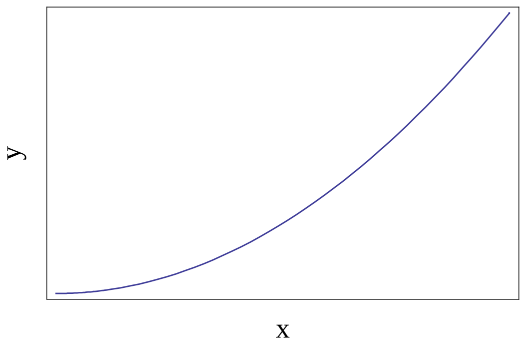
In this lab we will attempt to gather data that will allow us to judge which of these two models is best. One way we will analyze the data is to create some graphs. Before we start taking data let's think about what kind of curves each model predicts for certain types of graphs. We want to decide how we will construct the graphs, and then determine the curve that each model predicts for the graph. We will consider the following possible curves:



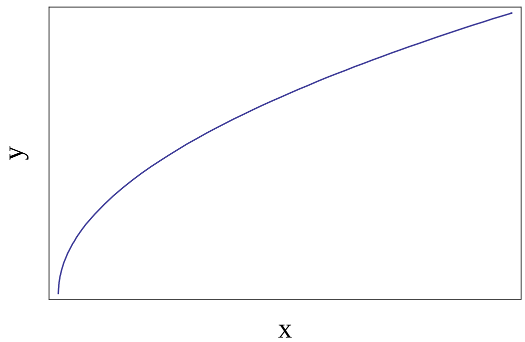
(a) Graph A



(b) Graph B



(c) Graph C



(d) Graph D

5. If we plot t on the x-axis and d on the y-axis, which curve does **Aristotle's Model** predict for our graph? Think about the equation that describes Aristotle's Model, and make the following substitutions: $t \rightarrow x$ and $d \rightarrow y$. Write down the result in the space below. Which of the graphs (A through D) could be a graph of this equation?

6. Describe the shape of the curve predicted by Aristotle's Model for a graph of d vs. t.
   (a) It is a straight line.
   (b) It is an upward-opening parabola.
   (c) It is a sideways-opening parabola.
   (d) It is an exponential curve.

7. If we plot t on the x-axis and d on the y-axis, which curve does **Galileo's Model** predict for our graph? Think about the equation that describes Galileo's Model, and make the following substitutions: $t \rightarrow x$ and $d \rightarrow y$. Write down the result in the space below. Which of the graphs (A through D) could be a graph of this equation?

8. Describe the shape of the curve predicted by Galileo's Model for a graph of d vs. t.
   (a) It is a straight line.
   (b) It is an upward-opening parabola.
   (c) It is a sideways-opening parabola.
   (d) It is an exponential curve.

9. If we plot t^2 on the x-axis and d on the y-axis, which curve does **Aristotle's Model** predict for our graph? Think about the equation that describes Aristotle's Model, and make the following substitutions: $t^2 \to x$ (or $t \to \sqrt{x}$) and $d \to y$. Write down the result in the space below. Which of the graphs (A through D) could be a graph of this equation?

10. Describe the shape of the curve predicted by Aristotle's Model for a graph of d vs. t^2.
    (a) It is a straight line.
    (b) It is an upward-opening parabola.
    (c) It is a sideways-opening parabola.
    (d) It is an exponential curve.

11. If we plot t^2 on the x-axis and d on the y-axis, which curve does **Galileo's Model** predict for our graph? Think about the equation that describes Galileo's Model, and make the following substitutions: $t^2 \to x$ (or $t \to \sqrt{x}$) and $d \to y$. Write down the result in the space below. Which of the graphs (A through D) could be a graph of this equation?

12. Describe the shape of the curve predicted by Galileo's Model for a graph of d vs. t^2.
    (a) It is a straight line.
    (b) It is an upward-opening parabola.
    (c) It is a sideways-opening parabola.
    (d) It is an exponential curve.

13. In the previous questions you should have found that Aristotle's model predicts a straight line for one type of graph. Which type (y vs. t OR y vs. t^2)? What is the slope of the straight line predicted by Aristotle's model for that type of graph? Note: your answer will be symbolic, not numerical.

14. In the previous questions you should have found that Galileo's model predicts a straight line for one type of graph. Which type (y vs. t OR y vs. t^2)? What is the slope of the straight line predicted by Galileo's model for that graph? Note: your answer will be symbolic, not numerical.

STOP: Check your answers on the previous two questions before proceeding.

To decide between these two hypotheses we must conduct a careful experiment to gather detailed data about how an object falls. We will measure the distance that an object falls as a function of time. We will then create graphs of d vs. t and d vs. t^2. We can then determine for which of these graphs the data seem to best fit a straight line. Using your answers to the previous questions you can then determine which model best fits the data. You can also determine the slope of the best-fit line and relate it to parameters of the model.

3 Setting Up the Free Fall Apparatus

Follow these steps to set up the free fall apparatus.

- Attach or move the electromagnet so that the bottom of the steel ball will line up with the 0 mark on the column's scale. If the electromagnet is held flush to the column then the bottom of the metal tab that hangs down from the electromagnet will be level with the bottom of the ball.
- Attach or move one of the photogates so that its beam lines up with the 20 cm mark. The top edge of the center notch in the photogate is level with the beam.
- Attach or move the other photogate so that it is near the bottom of the column. You will not be using this photogate, so you are just getting it out of the way.
- Plug the electromagnet and both photogates into the "Freely-Falling Body" socket on the back of the digital timer.
- Turn on the digital timer. Press the "function" button several times until the "g" indicator lights up.
- Screw the plumb line into the bottom of the electromagnet.
- Adjust the tripod so that the plumb line passes through the photogates and interrupts the beams.

4 Taking Data

Follow the steps below to obtain your experimental data.

- Remove the screw and the plumb line. Set the free-fall switch to "6 V" – this will turn on the electromagnet. Place the steel ball in the electromagnet. It should sit securely in the center.
- Hit the Clear button on the digital timer to zero the time (if needed).
- Clear the area near the column and switch the free fall switch on the timer to "release". The ball should fall through the photogates and land in the catcher at the bottom of the column.
- The timer should flash the number "1" and then a numerical value. This numerical value is the time it took for the ball to fall from the electromagnet to the photogate beam. Note that if the "ms" light is lit then this time is in units of milliseconds (ms). Record this time (in seconds, not ms) in the table below.
- Flip the free fall switch back to "6 V" and replace the steel ball in the electromagnet. Hit the Clear button on the timer.
- Repeat the measurement of the time until you have five measurements. Record all time measurements in the table below.
- Repeat this procedure with the top photogate set at 40 cm, 60 cm, 80 cm, and 100 cm. In each case perform five time measurements and record all results in your table.

Distance of Fall (m)	t_1 (s)	t_2 (s)	t_3 (s)	t_4 (s)	t_5 (s)
0	0	0	0	0	0
0.2					
0.4					
0.6					
0.8					
1					

5 Analyzing the Data

You are now going to create two graphs. One graph will have the time of fall on the horizontal axis and the distance on the vertical axis. The other graph will have the *square* of the time of fall on the horizontal axis and the distance on the vertical axis. You will use these graphs to determine whether Aristotle or Galileo was correct, and to determine the value of v (if Aristotle prevails) or a (if Galileo is victorious). Create these graphs using Excel. Set up your spreadsheet with a column for t values, a column for t^2 values, and then a column for d values. Note that for each value of d there will be 5 values of t and five values of t^2, so you should have a total of 25 rows of data. Use Excel to draw and determine the equation for the "best fit" line, as well as the R^2 value, for each graph. Make sure to give appropriate labels to each axes on each graph, and indicate the units for all axes.

STOP: Once you have constructed both graphs, please have them checked before you proceed.

15. Explain why we know the times for the first row of the data table without taking any measurements.

16. Record the equation of the best fit line , as well as the value of R^2, for your graph of d vs. t in the space below. Make sure to indicate the units for all numerical values that have units. (If you need help determining the units, ask.)

17. Record the equation of the best fit line , as well as the value of R^2, for your graph of d vs. t^2 in the space below. Make sure to indicate the units for all numerical values that have units. (If you need help determining the units, ask.)

18. Based on your analysis, which Model do you think better describes your data for the fall of the small metal ball? Give reasons for your answer.

19. If you found that Aristotle's Model was best, what is the speed with which the metal ball fell? If you found that Galileo's Model was best, what was the ball's acceleration as it fell? Refer back to the answers to questions 13 and 14, and the equation for your best fit line, to determine the appropriate quantity and make sure to include units. Record your answer below.

20. A wide variety of experiments indicate that Galileo's view is the correct one, and that if air resistance is negligible all objects fall to Earth with a constant acceleration $g \approx 9.8\ \mathrm{m/s^2}$. If you found the ball's acceleration, was it close to this value?

6 Reflection

21. We know that Galileo's Model ignores the effects of air resistance. Now we want to consider whether air resistance can explain the discrepancy (if any) between your measured acceleration and the accepted value of g. Will air resistance tend to increase or decrease your measured acceleration? Can air resistance explain your discrepancy? Explain.

22. Are there any situations in which Aristotle's Model might provide a better description of the fall of an object? If so, give one example of such a situation and explain why Aristotle's Model would be superior to Galileo's Model in that case.