Free Fall

Goals and Introduction

When an object is subjected to only a gravitational force, the object is said to be in "free fall". This is a special case of a constant-acceleration motion, and one that you have likely spent some time investigating in class. In this lab, you will quantify the motion of a falling object and use the results to calculate a value for the gravitational acceleration on Earth, g.

When objects move in Earth's atmosphere, they are also subject to a force due to air resistance. However, when the velocity of an object is small, it is fair to approximate that there is no air resistance force. This means that when we drop an object on Earth, while the velocity is small, the acceleration of the object would be constant and equal to g = 9.8 m/s^2 downward. The position and velocity of an object moving with a constant acceleration, a, can be modeled using the *kinematic equations*:

$$y = y_0 + v_0 t + \frac{1}{2}at^2 \qquad \text{(Eq. 1)}$$

$$v = v_0 + at \qquad \text{(Eq. 2)}$$

where v_0 is the initial velocity of the object, y_0 is the initial position of the object, and t is some amount of time after the initial values are recorded.

We normally use a right-handed coordinate system when modeling motion, where the positive y-axis points upward and the positive x-axis points to the right from our vantage point. This means that when an object is accelerating due to gravity, the acceleration would be negative because it would point downwards. So, for an object beginning at the origin with no initial velocity and subject only to a gravitational force, the kinematic equations become

$$y = -\frac{1}{2}gt^2 \qquad \text{(Eq. 3)}$$

$$v = -gt \qquad \text{(Eq. 4)}$$

where again, g = 9.8 m/s^2. Given that the object is starting at rest at the origin in this scenario, as the object falls it will be attaining negative positions in the coordinate system and have an increasing negative velocity. For example, if we drop an object from a height of 2.0 m above the floor and we put the origin of our coordinate system where the object begins, the object will be at a location of -2.0 m the instant it hits the floor.

Note that Eq. 3 and 4 do not depend on the mass of the object. This might seem counterintuitive since more massive objects are more difficult to accelerate, but recall that the gravitational force is greater on a larger mass. Thus, the resulting acceleration is the same as for a less massive object. A greater factor that affects our everyday experience with falling objects is air resistance, but if the objects have a similar size and shape, their air resistance effects should be similar and their accelerations should still be the same, as predicted by Eq. 3 and 4.

Today, you will measure the time necessary for an object to fall several distances, graph the results, and use your plot to determine a value for the gravitational acceleration on Earth. You can then compare your result to the accepted value to evaluate the effectiveness of your measurement process. You will also investigate whether or not the mass of the object affects its acceleration due to gravity.

Goals: (1) Gain further experience using the kinematic equations to investigate an object in free fall.
(2) Confirm the value of g on Earth and test for mass dependence.
(3) Use graphical analysis as a means to examine the kinematic equations.

Procedure

Equipment – stopwatch, 2 m stick, super ball, metal ball, foam mat, balance, Microsoft Excel

During this experiment, one lab partner should operate the stopwatch while the other partner drops the super ball or metal ball. Throughout the experiment, the origin of our coordinate system will be at the initial location of the object, meaning all final positions the instant before hitting the foam mat will be represented by negative values. Be careful retrieving the objects after they hit the mat, so as to not hurt yourself or others.

1) Place the foam mat on the floor and the bottom of the 2 m stick on top of it. Place the super ball in line with the top of the 2 m stick so that the bottom of the ball is at the 2 m mark. **Measure and record** what will be the final position of the ball (-2.0 m in this first scenario). Label this as y_A. **Record** the uncertainty in your measurement and label this as Δy_A.

2) **Measure and record** the time for the super ball to reach the mat. Practice this process several times before conducting your measurements. As simultaneously as possible, one partner should start the stopwatch as the other partner releases the ball. Then stop the stopwatch the instant the ball hits the mat. Label this result as t_A. **Estimate and record** the uncertainty in your time measurement. Label this as Δt_A. This is likely due to your reaction time. To react to a single event most people take about 0.2 s. How many times do you need to react in making this

measurement? Consider the answer to that question in estimating your total uncertainty for one measurement of the time to fall.

3) Repeat steps 1 and 2 until you have ten total measurements for the time to fall 2.0 m. **Record** your results for each trial.

4) Change the initial height to 1.75 m and repeat steps 1 through 3. Use the subscript "*B*" to label these results for position, time, and their uncertainties.

5) Change the initial height to 1.5 m and repeat steps 1 through 3. Use the subscript "*C*" to label these results for position, time, and their uncertainties.

6) Change the initial height to 1.25 m and repeat steps 1 through 3. Use the subscript "*D*" to label these results for position, time, and their uncertainties.

7) Change the initial height to 1.0 m and repeat steps 1 through 3. Use the subscript "*E*" to label these results for position, time, and their uncertainties.

8) Place the metal ball in line with the top of the 2 m stick so that the bottom of the ball is at the 2 m mark. **Measure and record** what will be the final position of the ball. Label this as y_{metal}.

9) **Measure and record** the time for the metal ball to reach the mat. As simultaneously as possible, one partner should start the stopwatch as the other partner releases the metal ball. Then stop the stopwatch the instant the ball hits the mat. Label this result as t_{metal}.

10) Repeat steps 8 and 9 until you have ten total measurements for the time to fall 2.0 m. **Record** your results for each trial.

11) Using a balance **measure and record** the mass of the super ball and the mass of the metal ball.

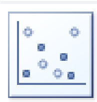
As always, be sure to organize your data for presentation in your lab report, using tables and labels where appropriate.

Data Analysis

Find the average (mean) value for your fall time data in each scenario (*A* – *E*) for the super ball. Label the results as $t_{A\text{avg}}$, $t_{B\text{avg}}$, $t_{C\text{avg}}$, $t_{D\text{avg}}$, and $t_{E\text{avg}}$.

HINT: In the following set of instructions, the red font instructions are meant to substitute for the immediately preceding black font instructions.

We want to use Eq. 3. to make a plot of final position (*y*) versus time squared (t^2) to determine the slope of the trendline through the data. Ideally, the slope would be (-1/2)*g*. **Create** a plot with *y* on the *y*-axis and t^2 on the *x*-axis. This should be done in Microsoft Excel. Square each of your average fall times and list them in column A. List the corresponding final positions (*y*) in column B. Click and hold the mouse button down while dragging the cursor to highlight all the data in both columns. (If you are using a Mac, see the red instructions for this step below) For a machine using Office for Windows, click on the "Insert" tab and then click on "Scatter" in the "Chart" section on that tab. Finally, select the scatter plot where the points are not connected:



(For Mac users) Click on the tab, or drop-down menu labeled "Insert" and select or click on "Chart". You must then selecte the X Y Scatter chart called "Marked Scatter". This should automatically create your chart on the spreadsheet. It should leave you in a tab called "Charts > Chart Layout"; if not, navigate to that tab now if able.

After you create the chart, click once on one of the data points. This should cause them to be highlighted. Then click on the "Layout" tab under "Chart Tools". Click on "Trendline" in the "Analysis" section of the tab and select "More Trendline Options". Click the box next to "Display Equation on Chart", and then click "OK".

(For Mac users) Under the "Analysis" section, you should see a button called "Trendline". Click on this and observe the options on the drop-down menu that appears. Select "Trendline Options". Be sure to click on "linear" since our data appear to be linear. On the left side of the window, click "Options" and check the box for "Display Equation on chart". Then, click on the "OK" button.

You should see an equation for the trendline on the chart. The number in front of the "x" is the slope. **Record** the slope as *m*.

Since Eq. 3 predicts the slope is (-1/2)*g*, multiply your slope by -2 and label your result as g_{exp1}.

Find the average (mean) value for your fall time data of the metal ball. Label the results as t_{mavg}.

Question 1: Compare your average time for the metal ball to that of the super ball in scenario *A* (so that they started at the same height). Does the mass of the object seem to affect the time to fall? Explain your answer.

Using Eq. 3, your average fall time (t_{mavg}), and the final position (y_{metal}), calculate the value of g. Label your result as g_{exp2}.

Error Analysis

Let us first compare our results for g to the accepted value, g = 9.8 m/s^2. Calculate the percent error for each of your experimental values.

$$\%err_{g1} = \left| \frac{g_{exp1} - g}{g} \right| \times 100\%$$

$$\%err_{g2} = \left| \frac{g_{exp2} - g}{g} \right| \times 100\%$$

Question 2: Evaluate your percent errors. How well do you think the experimental results matched the predictions? Which method of finding g came closest to the accepted value? What aspects of the procedure or measurement could have caused the difference? Explain.

In the Data Analysis section, you computed the average (or mean) values of the fall times for each scenario (A – E) involving the super ball. Compute the standard deviation and standard deviation of the mean for each scenario, using the ten fall time measurements and the averages you calculated in each case. If you do not remember how to do this, review the lab entitled Statistical Analysis of Data.

Question 3: Comment on the results of your statistical analysis. The standard deviation represents the average measurement error for the time collection process. It will have units of time. How does it compare to your estimated error in each scenario? Does the confidence in the mean values increase or decrease as the initial height of the ball is lowered? Explain your answer.

Questions and Conclusions

Be sure to address Questions 1-3 and describe what has been verified and tested by this experiment. What are the likely sources of error? Where might the physics principles investigated in this lab manifest in everyday life, or in a job setting?

Pre-Lab Questions

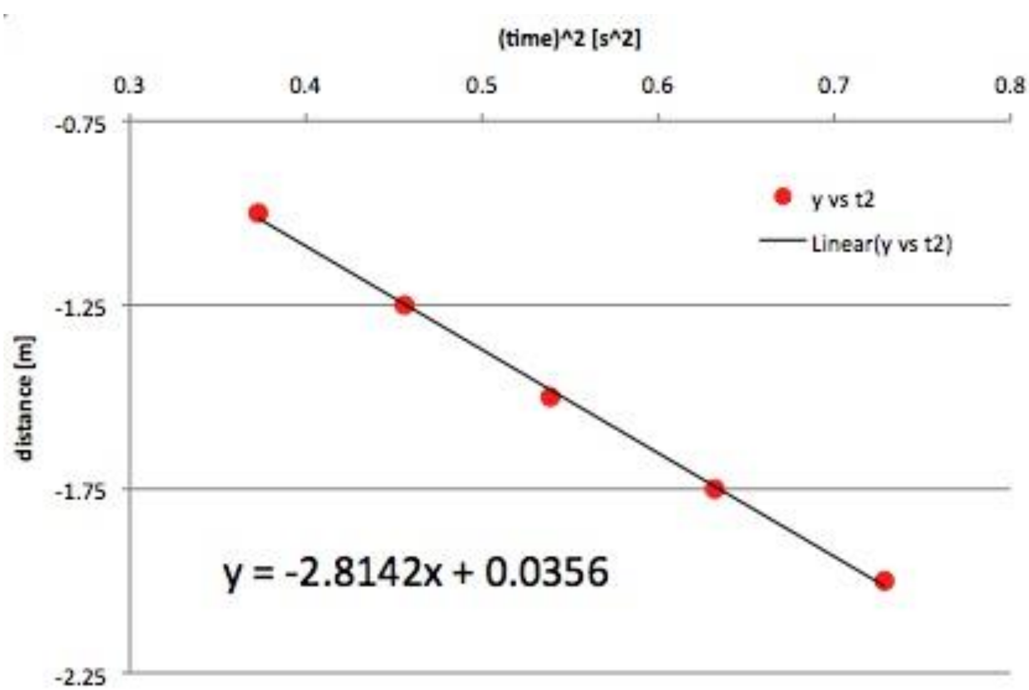
Please read through all the instructions for this experiment to acquaint yourself with the experimental setup and procedures, and develop any questions you may want to discuss with your lab partner or TA before you begin. Then answer the following questions and type your answers into the Canvas quiz tool for "Free Fall," and submit it before the start of your lab section on the day this experiment is to be run.

PL-1) A metal ball is dropped from rest. As the ball experiences free fall, what is its velocity, in m/s, at a time 1.00 s after it was released? *[Hint: consider the coordinate system described in the Goals and Introduction section.]*

PL-2) Considering the metal ball in free fall from PL-1, what is the position of the ball, in meters, at a time 1.00 s after it was released? *[Hint: consider the coordinate system described in the Goals and Introduction section.]*

PL-3) In their free fall experiment, Sasha and Malia measure g = 9.4 m/s^2. What is their percent error from the accepted value of g? *[Hint: answer as a number only, the percent symbol is implied. For example, for 33%, enter 33.]*

PL-4) Braaaap and Ptttthp do the Free Fall experiment on their home planet of Gwok-gwok-gwok, and obtain the following data graph. What is the magnitude of the acceleration due to gravity on this planet, in m/s^2? *[Hint: read the Data Analysis section]*.



PL-5) As the initial height of the ball is changed during the experiment, the acceleration due to gravity should

- increase rapidly.
- decrease slowly.
- increase slowly.
- remain unchanged.
- increase rapidly.