Gravity: How fast do objects fall?
Student Advanced Version

Kinematics is the study of how things move – their position, velocity, and acceleration. **Acceleration** is always due to some **force** acting on an object, in a car this force is provided by the engine or the brake pedal. Today, we will focus on a particular force that we experience constantly – the force of **gravity**. In this lab we'll use a computer program to mark the times at which washers on a string hit the ground, and use these measurements to calculate the velocity of the string and to see whether it accelerates. We'll also look at whether the **mass** of an object (the amount of "stuff" in it) affects how fast it falls.

Key Concepts:
- **Velocity** = change in position ÷ change in time
- **Acceleration** = change in velocity ÷ change in time
- Gravity accelerates all objects at the same rate (regardless of mass). This means that as an object begins to fall, it moves faster and faster (its velocity increases). Heavy and light falling objects will reach the ground at the same time
- An object moving with a constant acceleration (a) for a time (t) covers a distance (d) given by: $d = \frac{1}{2} at^2$
- When we want to test that two measured physical variables are related by a particular equation, we can often arrange the hypothesized equation to give a **linear relationship** between two variables that can be calculated from the experiment ("linearizing the data"), then check to see whether the data do in fact fall on a line. Unknown physical constants (eg: acceleration of gravity) can be extracted from the slope of the line.

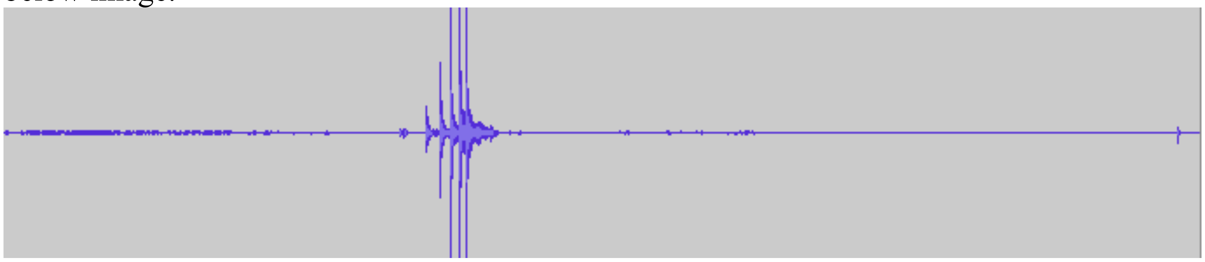
Part 1 – Distance versus Time for a Falling Object

In this first part you will measure the acceleration of gravity directly by calculating how the velocity of a falling object changes with time. You will use the microphone on your computer to accurately measure the time it takes for washers to fall different distances.

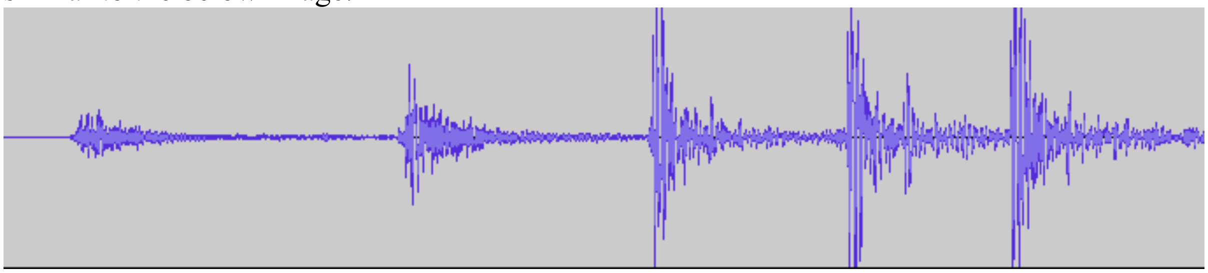
Procedure:
1. Your lab kit should include a long string with washers tied to it. One person should stand up and dangle the string so that it hangs down straight and so that the metal weight on the bottom is just touching the ground. The other person should **use a meter stick to measure the distance from the ground to each washer. Fill in the distance in the data table below. Also fill in the square root of the distance in the second column.**
2. **Place a large paperback book or workbook under a piece of aluminum foil on the floor. Place the computer on a chair near the aluminum foil.**

3. Make sure Audacity is up on your computer. **Hit the Record button** (button with the red circle) and **tap the aluminum foil with your finger a few times, to make sure you can see the sound being graphed on the screen.** You may need to adjust the microphone volume up to increase the signal or down to decrease the noise. The volume can get adjusted using the slider next to the microphone icon:

   Go to Edit->Undo to get rid of the test recording.
4. Two students should work together to carry out the experiment:
   Person 1: **dangle the string over the piece of aluminum foil so that the weight at the end is just touching the foil.** Stand on a chair if necessary.
   Person 2: **hit the record button on the computer** and tell Person 1 you have done so.
   Person 1: After you get the signal from Person 2, **let go of the string.** The washers should fall one by one onto the foil, with each one making a sound when it strikes.
   Person 2: **Stop the recording.**
5. Look at the Audacity display and **make sure that you can see 5 peaks on the graph corresponding to each of the washers hitting the ground.** If the signal looks too messy to make out the peaks, you may need to redo the experiment. It should look something like the below image.



6. To find the time at which each washer hit the ground, **position the cursor over the peak in Audacity (using the mouse or arrow keys).** To see the peaks more closely, use the mouse to highlight all the peaks and then zoom in by going to View->Zoom to Selection to look similar to the below image.



   Look at the bottom of the Audacity window. There should be a line that says "Selection Start:", make sure the time there is set to **hh:mm:ss + milliseconds.** These numbers give the time corresponding to the cursor. **In your data table, fill in the time at which each washer hit the ground.**
7. **Repeat steps 4 to 6 once more, recording the times in the column for trial 2.**

Data Table:

Distance (cm)	$\sqrt{\text{distance}}$	Time (sec), Trial 1	Time (sec), Trial 2

Q1. What does a time of 0 correspond to in this experiment?

You will now use this data to calculate an approximation to the acceleration of gravity. The formula for an object falling under constant acceleration is:

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

(Where *d* is the distance an object falls in time *t,* if it has acceleration *a*)

8. **Rearrange the formula to solve for time (*t*) in terms of the other variables** (get *t* by itself on one side of the equation). The result should look like some coefficient (that does not involve distance) times some function of distance

$$t = (\underline{\hspace{3cm}}) \times (\underline{\hspace{3cm}})$$

coefficient *function of d*

9. **What two variables (involving experimentally measured quantities) should we plot so that we would expect a linear relationship?**
   Remember, a linear relationship looks like:

   $$y = (\text{slope}) \times (x)$$

   Our y variable will be: ______________
   Our x variable will be: ______________
   We expect the slope of the line to be: ________________
   (Hint: *this will involve the acceleration variable)*
   You will use Excel to see if the data really does look linear and to find the slope of the line that best approximates your data.

10. Excel should be open on your computer. **At the top of the first column, enter the values of your x variable** (you have already calculated them in the Data Table above). Next to that, **in the second column, enter the values of your y variable from Trial 1. In column 3, enter the y variable values from Trial 2. Use the mouse to highlight all the numbers that you entered.**

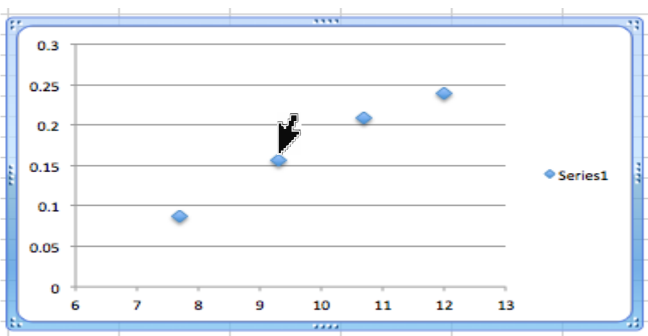
11. In the menu at the top of the screen, go to **Insert → Chart**. **Under chart type, select "XY (Scatter)". Click Finish.** Excel will show a graph with two series of data points. Each series of points corresponds to data from one trial.

Q2. Is the data what you expected, with the points from each trial falling on a straight line?

Q3. Are the two lines approximately parallel? Why would you expect this to be the case? (Hint: parallel lines have the same slope)

Q4. Why are the lines from the two trials offset from one another? What does the y-intercept correspond to here? (Hint: the y intercept is the time when distance fallen is 0)

12. **Click on the first series of data points to select it.** In the top menu, go to **Chart → Add Trendline**. Make sure "Linear" is selected. Then click on the Options tab at the top and click on the box that says **"Display equation on chart"**. Click OK. Excel has now drawn the line of best fit for your points and has shown you the equation of that line. **Repeat for the other series of data points.**



13. Fill in the equation for the line of best fit (remember, your y variable is time t and your x variable is square root of the distance, $\sqrt{d}$):

Trial 1:

y = __________ x + ______________ (t = __slope__ $\sqrt{d}$ + ______________)

Trial 2:

y = __________ x + ______________

Q5. What is the slope found by Excel?

Slope for Trial 1 = ____________

Slope for Trial 2 = _____________

14. **Go back to your expression for the slope in terms of the acceleration *a*. Set this equal to the slope you found and solve for the acceleration of gravity**!

Slope as a function of a (copied from step 9):

Measured acceleration of gravity (trial 1) = _____________
Measured acceleration of gravity (trial 2) = _____________

15. Find the average acceleration from your two trials:

Average acceleration = (acceleration$_{[trial\ 1]}$ + acceleration$_{[trial\ 2]}$)÷ 2 = ___________

Follow-up questions:

Q6. The real gravitational acceleration is 980 cm/s^2. What is the percent error in your measurement?

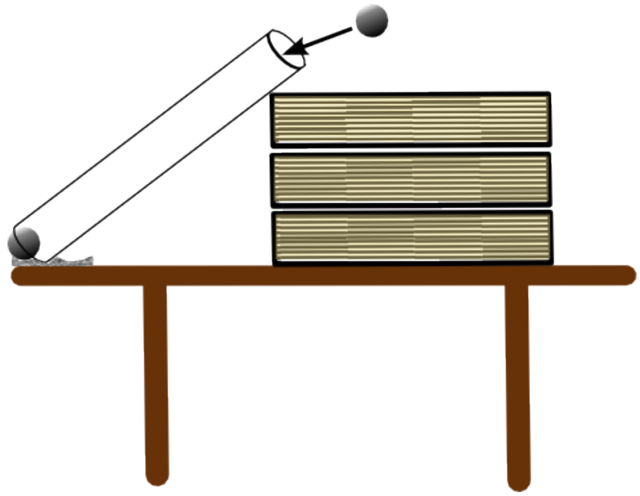
% error = (measured average acceleration - 980) ÷ 980 × 100 = _______________

Q7. Do the time intervals between the washers hitting the ground increase, decrease, or stay the same as more washers hit? What does this mean about the velocity of the string?

Q8. If you changed the spacing of your washers to all be 20cm apart and then repeated the experiment, would you expect the slope of the line to change? Explain why not or in which direction?

Q9. If you changed the spacing of your washers to 20cm apart, would you expect the time intervals between the different washers hitting the ground to change as compared to a 30cm separation? Explain why not or in which direction?

Part 2 – Gravity and Mass



In this part, you will measure the acceleration of gravity in another way, and also look at the effect of the mass of the falling object.

Procedure:

1. **Use 2 to 3 books to angle your paper towel tube to make a ramp near the edge of the table. Place a marble at the very edge of the table, right next to an open end of the tube.** If you have trouble with the marble rolling away from the edge, use a piece of aluminum foil to make a slightly rough surface for it to lie on.
2. **Roll another marble down the paper towel tube so that it knocks your first marble off the table. Place a piece of aluminum foil on the floor approximately where the first marble fell. Reset your ramp and marble at the edge of the table as before.**
3. Just like in Part 1, one person should be in charge of recording, and one person should perform the experiment. Make sure the microphone of your computer is near the marble on the edge of the table.
4. Person 1: **press the record button on Audacity**
   Person 2: **Roll the 2nd marble down the paper towel tube so that it knocks the first marble off the table**
   Person 1: **stop the recording**
5. Look at the graph of sound that you recorded and **find the peaks where the microphone heard the two marbles hitting and where the first marble hit the foil on the floor.** Zoom in and/or play back the recording if you aren't sure which peaks are the correct ones.

6. **Find the time interval between when the marble was struck and when it hit the floor**. **Fill this in as Trial 1 in the data table below. Repeat the experiment one more time for Trial 2.**

   Trial 1:
   Time when marble was struck: ____________
   Time when marble hit the ground: __________

   Trial 2:
   Time when marble was struck: ____________
   Time when marble hit the ground: __________

7. **Measure the height** from the floor to the table.
   Height from which marble fell: ______________*cm*

8. Use the formula for the distance (*d*) fallen in time (*t*) by an object with acceleration (*a*):

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

Solve for acceleration in terms of the other variables:

$a =$ ________________

9. Plugging in the height of the table for *d* and the measured time intervals for *t,* **calculate the acceleration of gravity from each trial of your experiment, and enter the values in the Data Table.**

10. **Now repeat the experiment, but this time use a ping-pong ball at the edge of the table. Fill in the data table as before.** Note: you may have to adjust the aluminum foil to make sure the ping-pong ball strikes it when it falls!

   Trial 1:
   Time when ping-pong ball was struck: ____________
   Time when ping-pong ball hit the ground: __________
   Trial 2:
   Time when ping-pong ball was struck: ____________
   Time when ping-pong ball hit the ground: __________

Data Table:

	marble	**ping-pong ball**
Time interval (Trial 1)		
Time interval (Trial 2)		
Acceleration (Trial 1)		
Acceleration (Trial 2)		

Follow-up questions:

Q10. Was there a significant difference in the time of falling for the ping-pong ball versus the marble?

Q11. Does the acceleration of gravity depend on the mass of the object?

Q12. Which traveled a greater distance overall in the time it took to reach the ground, the marble or the ping-pong ball? What does that mean about the horizontal velocity of each ball as it rolled off the table?

Q13. What would happen if you used fewer books to make a less steep ramp?

Horizontal velocity coming off the table would:	*increase / decrease / stay the same*
Time to hit the floor would:	*increase / decrease / stay the same*
Horizontal distance the ball travels would:	*increase / decrease / stay the same*

(Try the experiment, if you're not sure!)

Q14. If gravity gives all objects the same acceleration, then why does a sheet of paper fall slower than a pebble? Why does a skydiver with a parachute fall slower than one without? (both reasons are the same)

Q15. ***Challenge question:*** *Can you explain the answers to questions 3 & 4 using conservation of energy?*

(Hint: the kinetic energy of a moving object is $KE = \frac{1}{2}mv^2$ and the potential energy of an object at height *h* is $PE = mgh$ (where *m* is the mass, *h* is the height, *v* is the velocity, and *g* is the acceleration of gravity). The total energy of the system is conserved, which means the energy of the 1st marble as it rolls to the bottom of the ramp must equal the total energy of the two balls as they roll off the table.)