# Lab 2. Free Fall

## Goals

- To determine the effect of mass on the motion of a falling object.
- To review the relationship between position, velocity, and acceleration.
- To determine whether the acceleration experienced by a freely falling object is constant and, if so, to calculate the magnitude of the acceleration.
- To calculate the appropriate uncertainties and to understand their significance when analyzing data.

## Introduction

When an object is dropped from rest, its speed increases as it falls—that is, it accelerates. In this experiment you will characterize the motion of freely falling objects using an ultrasonic motion sensor. As with last week, a significant part of the experiment entails understanding the relationship between the acceleration, velocity, and position of an object. You will also employ the concepts of mean (or average) value, standard deviation, and standard deviation of the mean of a measured quantity. An introduction to these concepts is given in the Uncertainty/Graphical Analysis Supplement at the back of the lab manual.

## Effect of mass on the motion of a falling object

At your lab station locate the small yellow plastic ball and a steel ball of the same diameter. After recording the masses of the balls, hold the balls at the same height and drop them together. Note which ball (if either) reaches the floor first. Use the padded catch box to minimize damage to the floor by the steel ball. If the balls strike the floor at different times, consider how accurately you can release the balls at the same time. An experiment with two identical balls can indicate how small differences in release time affect your results.

Note that it is rare for students to be able to release the two balls such that they will indeed both hit the ground at the same time. So spend some time working carefully to determine if you can devise a method of dropping which will reliably result in the same time difference (or simultaneity) of landing. It is common for people to drop differently with their dominant hand than they do with their off-hand, so does the fall give the same result if you switch hands? How about if your lab partner drops instead of you, does the result change then?

Scientists have to devise methods which are consistent regardless of who performs the experiment, and often will work to vary environmental or experimental configurations which they believe are unimportant to the experiment in order to check for "hidden variables" (things which do impact your results, but were not initially considered relevant and thus ignored).

If you change the height at which the balls are released, does the result change?

Record the conditions and the observed results for each trial that you do. Based on your findings summarize your observations. What can you conclude regarding the effect of the mass on the motion of the falling balls?

Try dropping another object such as a pen or pencil along with the steel ball. How do the motions compare now? What conclusions can you draw from your observations?

Be sure that the notes you make in lab are sufficient for you to repeat the experiment later in the semester if asked to do so.

# Characterizing the operation of the motion sensor

Consult the Computer Tools Supplement at the back of the lab manual to learn how to connect the **motion sensor** to the computer interface box at your lab station. Knowing the name of your sensor is important to being able to properly set them up, as well as looking at where the cables connect to the PASCO 850 Interface. Once the sensor is connected, set up the Capstone software to simultaneously display graphs of position, velocity, and acceleration as functions of time.

The motion sensor works by sending out a sound wave pulse, and then listening for the same sound to return after reflecting off of a surface. This places two limitations on the sensor: A minimum range, which is half of how far sound can travel in the time between starting to generate the sound and being prepared to receive a return signal, and a maximum range, which is half of the distance sound can travel in the time between pulse generation (controlled by what you set the recording rate to).

I want you to be able to form arguments with the data from this sensor, that also means I want to know you believe the measurements from the sensor to be accurate. How can you ensure that when the sensor says a velocity was 0.38 m/s it was correct? Can you check in any other way to see if the velocity was not actually 0.35 m/s or 0.41 m/s?

## Calibration and Testing of equipment

Add a *digits* display to the Capstone program, and set it to display position (by clicking on the *measurement* button and selecting position). Turn on your sensor by clicking the *Record* button on the bottom left of the screen.

At this point, your instructions are to "play" with your setup. Figure out how the sensor works, convince yourselves that it **does** work. And then find the limitations of the sensor. By holding the basketball beneath the sensor, figure out what the minimum range of the sensor is. Do this by displaying a Digits display set to show position, and by using a meter stick to verify the measurement. Hold the basketball very close to the sensor and move it away until the position begins to change.

Verify that the position reading is accurate (where is it measuring from and to?), continue to move the ball away from the sensor and verify that position updates appropriately. Once satisfied that the sensor work, begin to move the basketball back toward the sensor, make note of when the position reading ceases to update accurately. *Remember: Everything you do is to be described in your notebook with sufficient detail that someone unfamiliar with the lab (no access to the lab manual) would be able to repeat your actions to verify they get the same data. So record a description of your setup, your actions before and during measurements, and your data.*

The reason we are doing this play with position displayed is simple: That is the only one of the three values you can verify with a second measure that you already have faith in, and have a similar precision in measuring the values. That being a meter stick.

Do not stress about recording absolutely everything you do during this exploratory phase. However, if you figure out something significant (like equipment limitations or capabilities), it is worth recording what you learned, and what supports that being true.

Different sensors in the room will have different minimum ranges, and each sensor will have different maximum ranges at different times based on your selected recording rate. Every time that you use one of these sensors, start by figuring out these limitations. Any attempt to measure outside of the minimum to maximum range means the data is useless.

Now take some data while moving the Basketball up and down under the motion sensor. Display this position, velocity, and acceleration data in a table. Starting from the position data in this table, determine how Capstone computes the velocity as a function of time. Which position values are used to calculate the velocity at a given time? Repeat this process for the acceleration calculation. Which velocity values are used to calculate the acceleration at a given time? Use this to determine which position values are used to calculate the acceleration at a given time. Show sample velocity and acceleration calculations in your lab notebook, taking care to label the time at which each position value used in the calculation was recorded.

Use this information to determine how fast the motion sensor can respond to changes in velocity and acceleration. If the velocity of an object suddenly (instantaneously) changes from one value to another, how long will it take the velocity reported by Capstone to reach the new value? How is this change reflected in the value of acceleration reported by Capstone? If the acceleration of an object instantaneously changes from one value to another, how long will it take the acceleration reported by Capstone to reach the new value?

Finally, determine how far away from directly beneath the sensor you are able to obtain an accurate measurement of the posiition of the ball. Does this distance from alignment change along with distance from the sensor (Can you be further off center when near to the sensor than you can when far from it, or vice-versa?)

# Characterizing free fall with a motion sensor

## Data acquisition

Hold the basketball under the motion sensor such that the top of the ball is greater than the minimum distance for your sensor. Make sure that hands, feet, stools, backpacks, and such are removed from the target area so the motion sensor "sees" only the basketball. Click on the "Start" button of Capstone to start the data taking process. Wait a few seconds before quickly removing your hand(s) and releasing the ball. Allow it to fall to the floor and bounce twice. Then click the "Stop" button to terminate data acquisition. Expand the graphs to display only the motion during the fall and through the second bounce. Check with your TA to make sure that you have a good set of data. If necessary, repeat the data taking process until satisfactory data is obtained. You may need to adjust the record rate in Capstone to get clean readings on acceleration. Be aware that changing your record rate may change your maximum range. Print out a copy of the three graphs on a single page in the "landscape" format to include in your notes.

## Qualitative analysis

Observe the acceleration-time graph. Expand the graph vertically so that the acceleration during free fall occupies most of the graph. Ignore the noisy regions during each bounce, when the ball contacts the floor. This means your data will NOT include the "peaks" of the bounce on the position graph, only the smooth curve between those peaks. Remember that velocity and acceleration update a few data points later than position due to how the sensor calculates the values. Avoiding the data around the point of contact with the floor is not cherry picking data, it is merely isolating the data we consider to those points we are 100% confident will demonstrate the physical scenario of interest (free fall).

What conclusions can you make regarding the acceleration of the basketball during the initial fall and between the first and second bounces?

After the first bounce, the ball is moving upward toward the motion sensor and slowing down before it speeds up again and bounces the second time. Explain the sign of the acceleration (negative or positive) during this interval both as the ball slows down while moving upward and speeds up while moving downward.

Is the velocity-time graph consistent with the observed acceleration during each segment of the ball's motion? Compare them using the definition of acceleration in terms of velocity.

## Quantitative analysis

The value of the basketball's acceleration can be found from the position data, from the velocity data, or from the acceleration data. If the kinematic equations describe the path of the basketball, each data set should give the same acceleration.

1. Use the position vs. time graph to determine the average acceleration between the first and second bounce with Capstone's curve fit function. Select some of the position data between

the first and second bounces using the "Highlight range of points in active data" (pencil) tool from the tools along the top of the graph. Be sure to select only data in the region where your velocity and acceleration data are consistent. From the kinematic equation, we expect the position of basketball to be described by an equation of the form $y = At^2 + Bt + B$: the quadratic equation. With the data selected, choose "Quadratic" from the Curve Fit menu (icon shows red line through blue points) along the top of graph. From your knowledge of the kinematic equations, compute the acceleration of the basketball in free fall from the constant $A$ in the curve fit. Capstone also displays the uncertainty in $A$. Use this uncertainty to compute the uncertainty in the acceleration. This uncertainty is called the standard error, and is equivalent to the standard deviation of the mean computed for a list of averaged numbers. (If the precision of your acceleration value is less than its standard deviation, ask your TA for assistance in obtaining more significant digits. Always make sure that your printout clearly identifies which data points were used in the curve fit. If Capstone does not make it clear, identify them by hand after you print the data.

2. Use the velocity vs. time graph to determine the average acceleration and its uncertainty between the first and second bounces. From the kinematic equations, we expect the velocity of the basketball during free fall to be described by an equation of the form $v = At + B$: a linear equation. Select the velocity data between the first and second bounces and choose "Linear" from the curve fit menu to obtain the slope of the velocity-time graph (the constant $A$). On your printout, identify the data points used to determine the acceleration. The uncertainty in this acceleration measurement is equal to the "standard error" reported by Capstone in the curve fit window.
3. The acceleration vs. time shows the acceleration value direction. One can simply select the data between the first and second bounce and check the mean and standard deviation buttons under the $\Sigma$ button along the top of the graph. Again, identify the data points used to determine the mean acceleration. The uncertainty in the mean value is calculated by dividing the standard deviation by the square root of $N$, where $N$ is the number of data points used to calculate the mean. You will have to count the points by hand. Capstone will compute the uncertainty for you if you use the "User Defined Fit" function in the Curve Fit function, then enter an equation of the form $y = A$ into the Curve Fit in the Tools Palette on the left side bar.
4. Print your graphs again, with the annotations requested so far included on them.
5. Did the acceleration values determined in this experiment agree with your expectations? Do they agree with each other? Use the quantitative test for consistency described in the "Uncertainty and Graphical Analysis: Using uncertainties to compare measurements or calculations" section of the lab manual. Briefly, we conclude that two measurements, $a_1$ and $a_2$, with uncertainties $u(a_1)$ and $u(a_2)$, are consistent if $t' = |a_1 - a_2| / \sqrt{u(a_1)^2 + u(a_2)^2} < 3$. You will need to compare the three accelerations measurements you made from the position, velocity, and acceleration data, respectively. You should also compare these measurements with the "expected" value of $a = g = 9.80$ m/s$^2$.
6. Are some acceleration values "better" (more precise or more accurate) than others? Explain your reasoning.

# Conclusion

Discuss what you have discovered about objects in free-fall. What did you expect to find? Did your experiment agree with your expectations? Did the various methods of determining the acceleration of falling objects give the same values? Discuss and explain, using your results for the experiment. You may wish to summarize all your experimental numerical results in a small table here, making it easier to refer to them in this part of your notes. How does the concept of uncertainty assist us in making logical conclusions?

| | **No Effort** | **Progressing** | **Expectation** | **Scientific** |
|---|---|---|---|---|
| **SL.A.a**<br>Is able to analyze the experiment and recommend improvements<br>Labs: 1, 2, 5, 10, 11 | No deliberately identified reflection on the efficacy of the experiment can be found in the report | Description of experimental procedure leaves it unclear what could be improved upon. | Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed. | All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. Justification is provided for certainty of no shortcomings in the rare case there are none. |
| **SL.B.a**<br>Is able to explain operation and limitations of measurement tools<br>Labs: 1, 2, 5, 10, 11 | At least one of the measuring tools used in lab lacks a clear identification of precision/limitation | All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed | All measuring tools identified with precision/limitation of each tool listed. Description of how to measure using some tools may be incorrect/vague, or precision may not be adequately justified. | All measuring tools are identified with proper precision values and thorough discussion of limitations. Descriptions on how to make measurements are complete and could be understood by readers with no prior familiarity with the measuring tools. |
| **SL.B.b**<br>Is able to explain patterns in data with physics principles<br>Labs: 1, 2, 5, 8, 10, 11 | No attempt is made to explain the patterns in data | An explanation for a pattern is vague, OR the explanation cannot be verified through testing, OR the explanation contradicts the actual pattern in the data. | An explanation is made which aligns with the pattern observed in the data, but the link to physics principles is flawed through reasoning or failure to understand the physics principles. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |

| | **No Effort** | **Progressing** | **Expectation** | **Scientific** |
|---|---|---|---|---|
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 2-7, 9, 12 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |
| **CT.B.a**<br>Is able to describe physics concepts underlying experiment<br>Labs: 1, 2, 5, 8, 10, 11 | No explicitly identified attempt to describe the physics concepts involved in the experiment using student's own words. | The description of the physics concepts underlying the experiment is confusing, or the physics concepts described are not pertinent to the experiment for this week. | The description of the physics concepts in play for the week is vague or incomplete, but can be understood in the broader context of the lab. | The physics concepts underlying the experiment are clearly stated. |
| **CT.B.b**<br>Is able to identify dependent and independent variables<br>Labs: 1, 2, 5, 11 | No attempt to explicitly identify any variables as dependent or independent | Some variables identified as dependent or independent are irrelevant to the hypothesis/experiment, or some variables relevant to the experiment are not identified | The variables relevant to the experiment are all identified. A small fraction of the variables are improperly identified as dependent or independent. | All physical quantities relevant to the experiment are identified as dependent and independent variables correctly, and no irrelevant variables are included in the listing. |
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 2-4, 6-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |

| | No Effort | Progressing | Expectation | Scientific |
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| **QR.B** Is able to identify a pattern in the data graphically and mathematically Labs: 1, 2, 5, 8, 10, 11 | No attempt is made to search for a pattern, graphs may be present but lack fit lines | The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented. | The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity - is the proportionality linear, quadratic, etc. Graphs shown have appropriate fit lines, but no equations or analysis of fit quality | The patterns represent the relevant trend in the data. When possible, the trend is described in words. Graphs have appropriate fit lines with equations and discussion of any data significantly off fit. |
| **QR.C** Is able to analyze data appropriately Labs: 1-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A** Is able to record data and observations from the experiment Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B** Is able to construct a force diagram Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |
| **WC.B** Is able to draw a graph Labs: 1, 2, 4-8, 10, 11 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

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Lab 2 Free Fall:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

☐ Quit Capstone and any other software you have been using.
☐ Straighten up your lab station. Put all equipment where it was at start of lab.
☐ Required Level of Effort.
 ☐ Complete the pre-lab assignment ☐ Arrive on time
 ☐ Work well with your partner ☐ Complete the lab or run out of time

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| SL.B.b | | QR.A | | IL.B | |
| CT.A.a | | QR.B | | WC.B | |

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| SL.B.a | | CT.B.b | | IL.A | |
| SL.B.b | | QR.A | | IL.B | |
| CT.A.a | | QR.B | | WC.B | |