Experiment 2:

Measurement of g

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Distance "D" Between Lower Photogate and Impact Sensor (m)	Measurements of g (m/s^2)
1.000 ± 0.001	9.78 ± 0.06
0.900 ± 0.001	9.72 ± 0.07
0.800 ± 0.001	9.75 ± 0.07
0.700 ± 0.001	9.79 ± 0.08
0.600 ± 0.001	9.75 ± 0.09

Introduction

The purpose of this experiment was to determine the acceleration of gravity by experimental analysis. In order to do so, a ball was dropped so that it fell through two photogate sensors, and landed on an impact sensor. The time that it took for the ball to fall from one photogate to the other was used to calculate the average velocity between the gates. Another measurement of average velocity was taken by analyzing the time that it took for the ball to fall from the second photogate to the impact sensor. Based on the two measurements of velocity, the average gravitational acceleration could be calculated. This experiment was repeated 10 times for 5 different starting heights, yielding 50 different measurements of acceleration.

In order to turn measured raw data into calculations of measured acceleration, average velocities for each trial were calculated as follows:

$$v_{1avg} = \frac{\Delta position}{time} = \frac{d}{T_1} \qquad \text{(Eq. 1.1)}$$

$$v_{2avg} = \frac{\Delta position}{time} = \frac{D}{T_2} \qquad \text{(Eq. 1.2)}$$

These velocity calculations were then used to derive an equation for determining the acceleration of gravity:

$$a_{avg} = \frac{\Delta velocity}{time} = \frac{\Delta v_{avg}}{T_{avg}} = \frac{v_{2avg} - v_{1avg}}{T_{avg}} \qquad \text{(Eq. 1.3)}$$

$$T_{avg} = \frac{T_1 + T_2}{2} \qquad \text{(Eq. 1.4)}$$

$$g = a_{avg} = \frac{2}{T_1 + T_2}\left(\frac{D}{T_2} - \frac{d}{T_1}\right) \qquad \text{(Eq. 1.5)}$$

Experimental Results and Data Analysis

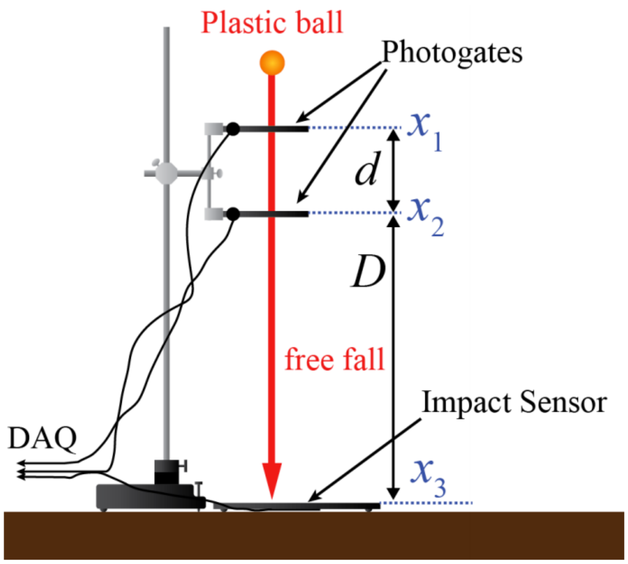

Figure 1: Experiment Setup: In order to perform the experiment, two photogates were placed with distance “d” between them, and an impact sensor was placed at a distance “D” from the lower photogate. When a ball triggered the sensors, data was sent through wires to a DAQ system, which relayed information to a computer. (Photo source: UCLA Physics 4AL Lab Manual by Professor Campbell)

During each trial, a ball was dropped so that each sensor, as shown in figure 1, was triggered on the way down. The times that the ball spent traveling distances “d” and “D” were recorded by the DAQ system. The data was used with equation 1.5 to calculate the measured value of gravitational acceleration “g”. The distance “D” was changed 5 times during the experiment to see if height would alter the measured acceleration. The calculated values of “g” for each of the 50 trials are shown in table 1.

	D = 1.000 ± 0.001 m	D = 0.900 ± 0.001 m	D = 0.800 ± 0.001 m	D = 0.700 ± 0.001 m	D = 0.600 ± 0.001 m
Trial 1	$9.78\,\frac{m}{s^2}$	$9.74\,\frac{m}{s^2}$	$9.74\,\frac{m}{s^2}$	$9.77\,\frac{m}{s^2}$	$9.74\,\frac{m}{s^2}$
Trial 2	$9.79\,\frac{m}{s^2}$	$9.71\,\frac{m}{s^2}$	$9.76\,\frac{m}{s^2}$	$9.79\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$
Trial 3	$9.77\,\frac{m}{s^2}$	$9.71\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$	$9.80\,\frac{m}{s^2}$	$9.72\,\frac{m}{s^2}$
Trial 4	$9.78\,\frac{m}{s^2}$	$9.71\,\frac{m}{s^2}$	$9.78\,\frac{m}{s^2}$	$9.78\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$
Trial 5	$9.76\,\frac{m}{s^2}$	$9.73\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$	$9.78\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$
Trial 6	$9.78\,\frac{m}{s^2}$	$9.71\,\frac{m}{s^2}$	$9.74\,\frac{m}{s^2}$	$9.79\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$
Trial 7	$9.79\,\frac{m}{s^2}$	$9.72\,\frac{m}{s^2}$	$9.76\,\frac{m}{s^2}$	$9.78\,\frac{m}{s^2}$	$9.74\,\frac{m}{s^2}$
Trial 8	$9.77\,\frac{m}{s^2}$	$9.73\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$	$9.81\,\frac{m}{s^2}$	$9.74\,\frac{m}{s^2}$
Trial 9	$9.78\,\frac{m}{s^2}$	$9.72\,\frac{m}{s^2}$	$9.77\,\frac{m}{s^2}$	$9.78\,\frac{m}{s^2}$	$9.76\,\frac{m}{s^2}$
Trial 10	$9.78\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$	$9.75\,\frac{m}{s^2}$	$9.78\,\frac{m}{s^2}$	$9.76\,\frac{m}{s^2}$

Table 1: Measurements of g: This table shows the calculations of g based on data taken from 10 trials at 5 different heights “D”. For each trial, the distance “d” between the two photogates was kept constant at 0.084 m. The values in the table were found by inputting raw data into equation 1.5.

As described in the lab manual, the systematic uncertainty in the calculations of “g” due to uncertainty in measurements “d” and “D” was determined by calculating the upper and lower bound values of “g” as shown below.

$$g_{max} = \frac{2}{T_1+T_2}\left(\frac{D_{best}+\delta D}{T_2} - \frac{d_{best}-\delta d}{T_1}\right) \quad \text{(Eq. 1.6)}$$

$$g_{min} = \frac{2}{T_1+T_2}\left(\frac{D_{best}-\delta D}{T_2} - \frac{d_{best}+\delta d}{T_1}\right) \quad \text{(Eq. 1.7)}$$

$$\delta g = \frac{g_{max}-g_{min}}{2} \quad \text{(Eq. 1.8)}$$

The calculated systematic contributions to δg are shown in table 2. Based on the ruler that we used, both δD and δd were 0.001 m.

Distance "D" Between Lower Photogate and Impact Sensor (m)	Systematic Contribution to δg (m/s^2)
1.000 ± 0.001	0.06
0.900 ± 0.001	0.07
0.800 ± 0.001	0.07
0.700 ± 0.001	0.08
0.600 ± 0.001	0.09

Table 2: Systematic Contribution to δg: This table shows the systematic contributions to δg for each distance D, based on calculations with equation 1.8.

In order to calculate statistical contribution to δg, equation 1.3 in the lab manual was used.

$$\delta g = \frac{\sigma_x}{\sqrt{N}} = \frac{1}{\sqrt{N}}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2} \qquad \text{(Eq. 1.9)}$$

The values δg that were calculated with equation 1.9 are shown in the table below.

Distance "D" Between Lower Photogate and Impact Sensor (m)	Statistical Contribution to δg (m/s^2)
1.000 ± 0.001	0.002
0.900 ± 0.001	0.005
0.800 ± 0.001	0.004
0.700 ± 0.001	0.003
0.600 ± 0.001	0.003

Table 3: Statistical Contribution to δg: This table shows the statistical contributions to $\boldsymbol{\delta g}$ for each distance D, based on calculations with equation 1.9.

By adding the systematic and statistical contributions to δg, an average uncertainty δg can be found for the trials that were done with each distance "D". The best average measurements of g, including systematic and statistical uncertainty, are shown in table 4.

Distance “D” Between Lower Photogate and Impact Sensor (m)	Measurements of g, Including Uncertainty δg (m/s^2)
1.000 ± 0.001	9.78 ± 0.06
0.900 ± 0.001	9.72 ± 0.07
0.800 ± 0.001	9.75 ± 0.07
0.700 ± 0.001	9.79 ± 0.08
0.600 ± 0.001	9.75 ± 0.09

Table 4: Measurements of g, Including Uncertainty δg: This table shows the calculated values for g based on the experimental trials for 5 distances “D” between the lower photogate and the impact sensor. The contributions to systematic uncertainty in table 2 were used as the uncertainty values for δg in this table due to the fact that each value for systematic uncertainty was over 10 times greater than the statistical uncertainty for the corresponding distance “D”.

In order to determine if there were any significant trends in the data, the data from table 4 was used to make a graph in excel, as shown below.

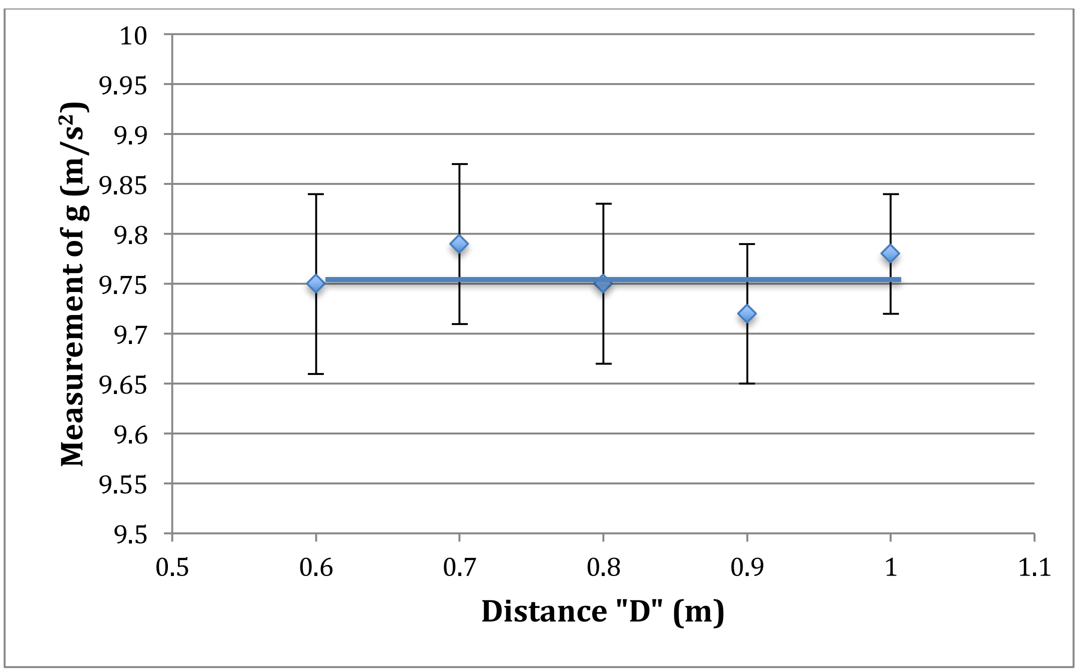

Figure 2: Trends in Measurements of g: The data from table 4 was used to plot measurements of g in this graph. An arbitrary line of slope zero was drawn to fit within the error bars of all points, indicating no significant trend in the data.

As seen in figure 2, a line of slope zero can be drawn so that it fits within the error bars of all points on the graph. This indicates that there is no significant trend in the 5 measured values of g.

If there was significant air resistance proportional to velocity, then an increase in "D" would show a decrease in measured acceleration. Dropping the ball from a greater height would allow more time for the ball to increase in velocity, as well as air resistance. This air resistance would create an upward force that would slow the descent of the ball, causing an increase in measured time between the second photogate and the impact sensor. This would cause lower values of g to be calculated for higher distances "D". Since the data gathered throughout the experiment did not follow this sort of trend, air resistance was likely not a significant factor.

As shown by comparing the data in tables 2 and 3, the uncertainty was most limited by systematic uncertainty, which was over 10 times greater than the statistical uncertainty. Seeing that most of the data yielded similar values, the main source of error was probably due to inaccurate measurement with the ruler, or due to flaws in the timing devices. These sources of error would have altered all of the data in a similar fashion.

Conclusion

The main goal of the experiment was to calculate the value of gravitational acceleration. The data that was gathered in table 4 shows that the measurements obtained throughout the 50 trials were all within range of each other. To visually display any trends in the data, a graph was created, as shown in figure 2. Since it was possible to fit a line of zero slope within the error bars of all points, no significant trend was found. The average measurement of gravity from all 50 trials, including propagation of uncertainty, was found to be $(9.76 \pm 0.2)\ m/s^2$, which is close to the true value of approximately $9.81\ m/s^2$.

Systematic uncertainty during the experiment was responsible for affecting all data in a similar manner. One main source of systematic uncertainty was due to measurements done with a ruler. It was difficult to keep the ruler perfectly straight, and to align it with the sensors in the photogates and the impact sensor. If distances "d" and "D" were measured to be slightly larger than they actually were, the calculated acceleration would have been larger, since the ball would have been recorded as traveling faster through a larger distance. Conversely, if the distances measured were smaller than the true distances, the calculated acceleration would be smaller, since the ball would have been recorded as traveling slower through a smaller distance. One way to fix this would be to use tools to keep the ruler lines perfectly horizontal and steady so that accurate measurements could be recorded, or to use a more accurate ruler.

Another source of systematic uncertainty was due to the ball not hitting the ideal spot on the impact sensor. Although there was a marking on the sensor, the marking may not have been exactly above the most sensitive spot. If the marking was far away from the true position, there would likely be a delay in the signal, causing a larger time "T_2" to be recorded. This larger time would cause a lower acceleration to be calculated. A more accurate marking would cause the impact signal to be sent to the DAQ system faster, which would lead to a quicker, and more accurate, recording of acceleration. One way to fix this would be to use a smaller impact sensor with less surface area, which would not rely on the ball hitting a sensitive spot.

Extra Credit

One source of systematic error was likely due to imperfect measurements by the impact sensor. Each time that the ball hit the platform, the impact was not immediately recorded due to flaws in the design of the sensor. In order to quantify this effect, a ball can be dropped repeatedly from a set height, with the impact sensor at a different position each time.

Before starting, the ball should be centered so that it hits the point that is marked on the platform when dropped. By moving the platform along the horizontal plane, and repeating the experiment, a graph can be created that shows the relationship between the distance of the ball from the marking on the sensor and the time that it took for the ball to fall from the second photogate to the impact sensor. If the points on the graph follow a trend, such that the larger distances showed larger recorded times, a trend line can be created. The slope of this trend line would give distance divided by time, which would provide a measurement of the speed of signal propagation in the sensor.

Since it is impossible for the sensor to record impact before it occurs, errors in measurement always resulted in delays. These delays manifested themselves in the systematic uncertainty by causing longer times to be recorded, which would have caused smaller measurements of g to be calculated. These erroneously small values would have altered all measurements similarly. In order to reduce uncertainty due to the sensor, the results of the test should be used to ensure that the most sensitive spot on the sensor's surface, which produced the smallest time delay, is marked correctly. Another solution would be to get a different impact sensor that reacts faster upon impact, or has a smaller surface area.