PHY 123 Lab 3 - Projectile Motion

The purpose of this lab is to study projectile motion of an object which is launched horizontally and drops a certain height before it hits the ground.

Important! You must print out the 1 page worksheet you find by clicking on this link. Take it with you to your lab session or you will be penalized. Before you leave the lab it must be collected by your Primary TA. It will be graded and returned to you at the next Lab.

Print out the .pdf version of this Lab 3 manual and take it to your lab session. It is here.

Video

Equipment

- ramp shaped like a “ski jump” with a horizontal positioning screw Make sure you know what is the “pitch of the screw thread” on the one you use!
- clip (can be moved) on the inclined ramp for placing the steel ball at reproducible position(s)
- steel ball
- photogate
- LabPro interface box (photogate -> computer)
- computer
Introduction

This experiment presents an opportunity to study motion in two dimensions. We investigate projectile motion, which can be described as accelerated motion in the vertical direction ("y") and motion with constant velocity in the horizontal direction ("x"). Review the material in Knight, Jones and Field, *College Physics: A Strategic Approach*, 2nd ed. (KJF2), Chap. 3.6 and 3.7, especially Example 3.11 on p. 86. (If you don't have a copy, you will find one bolted to a table in the A-131 Help Room on the A-level of the Physics building; copies are also on closed reserve in the Math/Physics Library on the C-level.)

An object launched horizontally with a velocity $v_x$ and dropping a height $h$, has the following relation between its horizontal distance traveled and $v_x$:

$$ x = v_x \sqrt{\frac{2h}{g}} $$

(3.1)
Determine experimentally the relationship between horizontal distance and initial velocity

You will establish the proportionality constant between the horizontal distance, $x$, and the horizontal component $v_x$ of the initial velocity (which, by the setup, is in the x-direction) by studying the motion of a steel ball launched from a ramp. Because there is no acceleration of the ball in the x-direction (if we ignore air friction and rolling friction on the ramp), the horizontal component of the velocity of the ball (measured using the photogate) remains constant until the ball hits the floor. The following are the important steps in getting the experiment underway.

1. Measure the height, $h$, the vertical distance from the bottom of the ball (when it's stationary at the end of the ramp) down to the floor and record it on your worksheet. Use the “poor man’s plumb bob” (string with paper clip attached) to find the point on the floor that is vertically directly below the point where the plumb-bob string touches the pulley tangentially. Assume that $h$ has an absolute uncertainty of 2 mm.

2. **Think of parts (2) through (5) as a long subsection you must read carefully.** Measure the “effective diameter” $d_{eff}$ of the steel ball. “Effective” refers to the diameter actually “seen” by the photogate. The effective diameter is NOT the same as the actual diameter that you would measure “mechanically” with a vernier or dial caliper or a screw micrometer. You should now be wondering why they are NOT the same. The dominant part of the answer is this: It depends on where on the ball the light beam in the photogate strikes-and-is-blocked-by the ball. If the position and angles of the photogate are adjusted so that the light beam strikes both the front of the ball and the back of the ball at points that lie on the same “equator”, which has “the diameter” instead of a “chord” as its through-the-ball dimension, then the effective diameter you measure should be close to the actual diameter. The measurement of $d_{eff}$ may be accomplished by using the rotary-screw device to move the photogate from the front to the back of the steel ball (kept stationary for this measurement) on the launching ramp. Make sure your platform with the ramp is solidly clamped to the lab bench when you turn the wheel that turns the screw to displace the photogate.

3. Additional warnings: You need to know how the platform on the screw device moves with each turn of the screw handle. There are likely two different screw devices being used in the different setups. One of them has a “pitch” of 1 mm, which means each turn of the screw moves the platform 1 mm. The other screw device, which looks pretty much the same, has a different “American measure” screw called a $\frac{1}{4} - 28$ screw (in American slang, a “quarter-twenty-eight screw”), which means it has a 1/4 inch diameter and 28 threads per inch so in one turn the platform moves 1/28 of an inch. **Make sure you know which screw-device you have. Put the appropriate check mark on your worksheet to indicate which kind of screw device you are using.**

4. When doing the measurement with it, **BEWARE of backlash.** If you’re turning the screw-wheel clockwise, say, after a turn or two the platform will move smoothly and continuously as you rotate the screw-wheel. If you stop, however, and then turn the screw-wheel counter-clockwise, you'll notice that the screw-wheel feels “very loose” and doesn't turn the screw the other way until you’ve moved the screw-wheel through some non-negligible angle. That's called “backlash”, and it's a common feature of screw-driven systems. The way to avoid its consequences is to do your measurement always “in one direction”, either clockwise or counterclockwise. Make sure your “overshoot” the position you want to start at and then “come back to it” and continue to do the measurement in that direction. This minimizes the effect of backlash.

5. The effective “front” and “back” of the ball are found, respectively, when the photogate is blocked or
unblocked as seen by the LED (light emitting diode) on top of the photogate. The LED is brightest when the gate is blocked and dimmest when the gate is unblocked. How do you read the displacement of the platform on the screw device? The “crude” way is to use the length scale attached to the platform. The “fine” way is to use the “rotational” scale on the screw wheel, but with this method you MUST avoid the effects of backlash. Remember for one of the screw devices, one turn is 1 mm, so, say, half a turn would be one-half mm; two turns would be 2 mm, etc. For the other screw device, half a turn would be one-half of 1/28 of an inch, etc. You can easily determine a small fraction of one rotation. How small? Try it out. This will give you one contribution to your estimate of the uncertainty in the effective diameter. Record your measurement of the effective diameter on your worksheet but ONLY AFTER you have tried to adjust the position and orientation angles of the photogate to maximize the effective diameter. Once you have done this maximization procedure, record the value of the effective diameter in the proper units on your worksheet. For the uncertainty in the effective diameter, don't just “assume” it to be some arbitrary value, say, 1 mm. Try to make your own best estimate of the uncertainty. Try repeated measurements of $d_{eff}$ and see how much they vary. Find a mean value and a standard deviation of the mean. Use what you (should have!) learned from the Lab 1 manual, *Uncertainty, Errors and Graphs*. 

**Note that once you have measured the value of $d_{eff}$ for your setup, you must NOT change the position or orientation angles of the photogate.** Shifting the photogate will change $d_{eff}$ and you don't want to change it after you made the effort to maximize it and measure it carefully! You should have been thinking all along about WHY you should try to maximize $d_{eff}$. HOW does this improve the data you will get? Think about this.

- Drop the steel ball from the lowest mark on the inclined ramp and note approximately where it lands on the floor. Then repeat this for the ball being dropped from highest mark on the inclined ramp. Tape the carbon paper with a piece of white paper underneath it to the floor so that the ball will hit the carbon paper and make a dark spot on the white paper no matter where it is launched on the ramp.

- Now connect the photogate output (But DON'T move the position or orientation of the photogate!) to the interface box by plugging its cable into the top socket (labeled “DIG/SONIC 1”) of the black interface box (“LabPro”). Test the photogate: block the photogate beam with your finger and see the red light on the cross bar of the photogate turn on (or, at least, get much brighter).

![Photo gate: red light]

- Turn on the computer and check the system; double click the icon “Exp3_t1_t2”. A window with a spreadsheet on the left (having a “Time” column) comes up. On top is a window called “Sensor Confirmation”. It should show the following kind of information (though it may be displayed a bit differently):

<table>
<thead>
<tr>
<th>Sensor Specified In File:</th>
<th>Sensor To Set Up:</th>
<th>Where:</th>
<th>Use:</th>
</tr>
</thead>
<tbody>
<tr>
<td>✔ Photogate</td>
<td>Photogate</td>
<td>DIG1 on LabPro ✔</td>
<td></td>
</tr>
</tbody>
</table>

[If you don’t see the above information, do the following: Click Experiment→Set Up Sensors→Show All Interfaces→DIG/SONIC1: you can check the photogate by blocking it and seeing “Unblocked’ go to “Blocked”.

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Click "Close".

- Click OK.
- Click Experiment→Start Collection.

- Move the clip to a position that will allow the ball to be placed reproducibly at the position of the lowest mark on the ramp. When you place the ball there and then release it (with the computer prepared as above to collect data), the computer will record the time \( t_1 \) when the ball enters the light beam of the photogate and the time \( t_2 \) when the ball leaves the light beam of the photogate. The difference \( t_2 - t_1 \) is the time the effective diameter \( d_{\text{eff}} \) of the ball, which you already measured, takes to traverse the beam of the photogate. You measure the horizontal distance \( x \) for the projectile motion of the ball in the following way: you hang the plumb bob from the end of the ramp and measure the distance between the point where the plumb bob touches the floor and the mark the steel ball landing on the carbon paper makes on the white paper.

**Warning:** Do not shift the position of the paper on the floor until you are finished with all your measurements. That paper must remain in the same position. Do you know WHY?

- When you change the "launch position" of the ball, you will be changing the velocity of the ball through the photogate. Each time the ball passes through the photogate, the time pair \( t_1, t_2 \) appears on the screen and you record the difference \( (t_2 - t_1) \) in the table on your worksheet. These time differences allow you to measure the initial of the velocity of the ball for each launch. For each position mark on the ramp, drop the steel ball 3 times and record the difference \( (t_2 - t_1) \) and the distance measurement. For each position mark, be careful to position the steel ball reproducibly at the same launch location on the ramp. (Since there are 5 position marks on the ramp, you should have a total of 15 time measurements and 15 distance measurements).

A tool is provided to help you make some calculations from the data in your table. For each mark on the ramp you Eq. (E.5) from the Lab 1 manual is used to calculate the average of the values of \( t \) and \( x \); enter them into Table 2. **Warning:** You should enter all distance in meters, not cm. Eq. (E.5b) from the Lab 1 manual is used to calculate the uncertainty for the average \( t \) and \( x \). To calculate the horizontal velocity, the formula \( v_x = \frac{d_{\text{eff}}}{t_{\text{avg}}} \) is used, and to calculate the uncertainty for \( v_x \), Eq (E.7) from the Lab 1 manual is used.

You actually don’t need to do all these calculations. Just enter your recorded values below, click submit, and the calculation tool with provide the desired values on a new window tab.

\[
\begin{align*}
  &d_{\text{eff}} = \boxed{\phantom{0000}} \pm \boxed{\phantom{0000}} \text{ m} \\
  &\text{From lowest point on ramp} \\
  &t_1 = \boxed{\phantom{0000}} \text{ s} \quad x_1 = \boxed{\phantom{0000}} \text{ m} \\
  &t_2 = \boxed{\phantom{0000}} \text{ s} \quad x_2 = \boxed{\phantom{0000}} \text{ m} \\
  &t_3 = \boxed{\phantom{0000}} \text{ s} \quad x_3 = \boxed{\phantom{0000}} \text{ m} \\
  &\text{From 2nd lowest point on ramp} \\
  &t_1 = \boxed{\phantom{0000}} \text{ s} \quad x_1 = \boxed{\phantom{0000}} \text{ m} \\
  &t_2 = \boxed{\phantom{0000}} \text{ s} \quad x_2 = \boxed{\phantom{0000}} \text{ m} \\
  &t_3 = \boxed{\phantom{0000}} \text{ s} \quad x_3 = \boxed{\phantom{0000}} \text{ m} \\
  &\text{From 3rd lowest point on ramp} \\
  &t_1 = \boxed{\phantom{0000}} \text{ s} \quad x_1 = \boxed{\phantom{0000}} \text{ m}
\end{align*}
\]
t2=  s  x2=  m

From 4th lowest point on ramp

From highest point on ramp

t1=  s  x1=  m

t1=  s  x1=  m

t2=  s  x2=  m

t2=  s  x2=  m

t3=  s  x3=  m

t3=  s  x3=  m

Copy the values the computer gives you into the second table on your worksheet. Once you have put your values there you need to make a plot of $x_{avg}$ on the vertical axis ($y_1, y_2, y_3, y_4, y_5$) versus $v_x$ on the horizontal axis ($x_1, x_2, x_3, x_4, x_5$) using the plotting tool below. Should you include the point (0,0) in your fit (making it a “constrained fit” in the language of the Lab 1 manual) this time? Hint: Ask yourself what is the distance traveled in the $x$ direction if the horizontal velocity is zero.

x axis label (include units): 

y axis label (include units): 

Check this box if the fit should go through (0,0). 

(Don't include (0,0) in your list of points below, it will mess up the fit.)

What kind of uncertainties are you entering below? None 

<table>
<thead>
<tr>
<th>x1:</th>
<th>+/-</th>
<th>y1:</th>
<th>+/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>x2:</td>
<td>+/-</td>
<td>y2:</td>
<td>+/-</td>
</tr>
<tr>
<td>x3:</td>
<td>+/-</td>
<td>y3:</td>
<td>+/-</td>
</tr>
<tr>
<td>x4:</td>
<td>+/-</td>
<td>y4:</td>
<td>+/-</td>
</tr>
<tr>
<td>x5:</td>
<td>+/-</td>
<td>y5:</td>
<td>+/-</td>
</tr>
</tbody>
</table>

Now you need to calculate the value of the acceleration due to gravity from the slope of your graph. That slope, which we shall call $k$, is related to $g$ through Eq. (3.1) of this Lab 3 manual, viz., $k = \sqrt{\frac{2h}{g}}$. We can rewrite this equation as

$$g = \frac{2h}{k^2}$$

(3.2)

Now you need to calculate what the value of $g$ measured earlier. Be careful: If you measured your value of $h$ in centimeters, you must convert it to meters so that your value for $g$ has units of m/s².

Your final task is to estimate the uncertainty in your measured value of $g$. Both $h$ and $k$ have a certain degree of
uncertainty and, strictly speaking, you should take both into account in your estimation of the uncertainty in \( g \). You can find the relative uncertainty in \( g \) from the relative uncertainty in \( h \) and \( k^2 \) using Eq. (E.7) from the Lab 1 manual. The relative uncertainty in \( k^2 \) is obtained from the relative uncertainty in \( k \) using Eq. (E.8) from the Lab 1 manual. You can then arrive at an expression for the uncertainty in \( g \):

\[
\Delta g = g \sqrt{\left( \frac{2\Delta k}{k} \right)^2 + \left( \frac{\Delta h}{h} \right)^2}
\]

(3.3)

Sometimes, when we combine relative uncertainties like this, we can neglect one of them if it is much smaller than the other. Below there is a tool that calculates the uncertainty in \( g \) using both the uncertainties in \( h \) and \( k \), just the uncertainty in \( k \), or just the uncertainty in \( h \). Enter your values (including your measured value for \( g \), not the known, “accepted” value) and click submit. The computer will display the three uncertainty estimates. Based on these three values can you conclude what is the most significant source of uncertainty in the experiment? Can you think of ways you could reduce this uncertainty?

Finally, you should check whether your measured value of \( g \) is consistent with the known, accepted value of 9.81 m/s\(^2\). To do this you have to KNOW what it means for two experimental quantities “to be consistent”. And we’re swindling you a bit! What does “The accepted value of 9.81 m/s\(^2\)” mean, anyway? You may not have known until know that the value of \( g \) depends on where you are on the Earth AND how far above the (local) surface of the Earth you are. The former comes from variations in both the density of rock and other stuff below where you are and from local variations in the topography, e.g., are you in a deep valley or on a high plateau or near sea level? Go to the table at the bottom of the web page here to see values of \( g \) at various locations on the earth. It's not “constant”; it varies! (Question: Can you see “systematic” variation of \( g \) as the values in one of the columns change? Hint: What's the variation with latitude? Once you notice it, can you explain it?) Geoscientists have agreed on a so-called “standard value of gravity” \( g_n = 9.80665 \) m/s\(^2\) that is a kind of world-average value for \( g \). Note that this rounds up to 9.81 m/s\(^2\), and that is what we're calling, for this experiment, the “accepted value” of \( g \). (It is NOT a “theoretical” value for \( g \). It is determined from experimental measurements!) Thought to ponder: What's the uncertainty in \( g_n \)? Does the question make sense?

When have completed all these tasks, you are ready to discuss your results and conclusions with your TAs.