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# Laboratory 5: motion due to gravity

*Hypothesis:* An object moving predominantly under the influence of gravity (falling, rolling) increases its speed as it falls or rolls, and does so at a constant rate.

*Goals:* Understanding how to characterize motion in terms of velocity and acceleration; linearizing mathematical relationships, design of experiments.

## 1 Introduction

As you have read or discussed in class, your *average velocity* ($v$) is the rate at which your position changed, or how far you went (in net) divided by the how long it took. If you covered a distance of 1 m in 0.5 s, your velocity would be 1 m/0.5 s=2 m/s. Your *average acceleration* is how much your velocity changed over a certain length of time. If you sped up from 2.0 m/s to 4.0 m/s in 0.5 s, then your average acceleration is (4.0 m/s − 2.0 m/s) / (0.5 s) = 4 m/s/s (more commonly written as $4\,\mathrm{m/s^2}$).

An object under the influence of gravity has a constant acceleration. That means that if we let an object fall or roll under the influence of gravity, its average velocity will increase by the same amount as each second goes by (about 10 m/s per second for objects falling). However, its average position will increase more and more as each second passes. Think of it this way: the first meter an object falls from rest it speed up to about 10 m/s. For the second meter, it *already starts* at 10 m/s and continues to speed up. Therefore, it can cover the second meter faster than the first, the third still faster, and so on.

The present experiment aims to test this by rolling small spheres down an incline.

## 2 Equipment

- 1 m long rail with center groove
- ruler
- marble
- stopwatch (i.e., your phone)
- mechanism to record and plot data

## 3 Procedure

The basic idea is to make a ramp of fixed angle, and let the marble loose from varying lengths along the incline, timing how long it takes to reach the bottom. The details of how to accomplish this are left up to you. Keep in mind that the more variables you can control, and the better you can reproduce your measurements, the better your experiment will be. Be systematic!

Here is a basic outline of a *suggested* procedure, which is certainly lacking in details you will need to fill in to make accurate measurements.

1. Construct a ramp using the optical rail and items in the classroom. Record the height of the end of the ramp and its overall length so the angle could be computed if necessary.
2. Put something at the end of the ramp to stop the marble. You will thank us.
3. Place a marble in the central groove at a given distance along the ramp (say, 100 cm = 1 m to start).
4. Release, and time how long it takes to reach the bottom of the ramp. You may want to make three measurements from the same distance and average the results to improve your accuracy and reduce the effects of your reaction time. You may want to have one person release ("Go!") while another does the timing.
5. Note: the bottom of the ramp is not at the 0 cm marking. Either the person timing should watch when the marble crosses the 0 cm mark, or you should add on the corresponding distance to the end of the ramp so your distances are accurate. Do what you will to ensure the recorded distances and times correspond.
6. Repeat this for 8-10 distances along the ramp, keeping a table of length and time recorded.
7. While it may be easier to record distances in cm, *be sure to make a new column with the data converted to meters* for your data analysis.

You will need to turn in your raw data and ramp measurements from this section. This can all be in an Excel/Google Sheets document if you like.

**Question 1.** Is a steep or shallow ramp more advantageous in terms of experimental accuracy? Consider "steep" to be raising your 1 m rail by around 30 cm on one end, and "shallow" to be a raise of 10 cm or less. Hint: which measurement limits your accuracy?

**Question 2.** Do you think it makes a difference if we were to use a hollow sphere or a cylinder instead of a solid sphere? How would you test this?

## 4 Data Analysis

### 4.1 Time and distance

As discussed in your class and in the text, we know how much distance $L$ an object covers in a certain amount of time $t$ when subjected to constant acceleration $a$. While the details of the acceleration in this experiment are complicated slightly by the ramp angle and rolling motion, it is true in spite of these factors that the acceleration should be constant. With a constant acceleration $a$, what we found was

$$L = \frac{1}{2}at^2 = (\text{constant})t^2 \tag{1}$$

What this means is that a plot of $t^2$ (x axis) against $L$ (y axis) should give a straight line, the slope of which relates to the acceleration.

- Plot $t^2$ (y axis) vs $L$ (x axis). (You will need a new column to calculate $t^2$. If you end up with $t^2$ on the y axis and can't fix it, that is fine, just make a note of it.)
- Add a linear trend line, and if you know how, set the intercept to zero (because covering zero length should take zero time). If you don't know how, ask for help. How good is the fit, qualitatively?

### 4.2 Velocity and time

It is also true that the average speed should change proportionally with time, i.e., for each second the object falls or rolls, the speed increases by the same amount. That means a plot of average speed versus time should be a straight line.

- The average speed for a given run is length divided by time, $L/t$. Make a column for this.
- Plot $v = L/t$ (y axis) versus $t$ (x axis).
- Add a straight line trend line, and if you know how, set the intercept to zero (covering zero length should take zero time). How good is the fit, qualitatively?

### 4.3 Velocity and distance

Now, if $v$ is proportional to (scales as) $t$, and $t^2$ scales as the distance covered $L$, it must be true that $v$ is proportional to $\sqrt{L}$ (or, equivalently, that $v^2$ is proportional to $L$).

$$
\begin{aligned}
& v \propto t && (2)\\
& L \propto t^2 && (3)\\
\text{therefore,} \quad & v \propto t = \sqrt{t^2} \propto \sqrt{L} && (4)
\end{aligned}
$$

Here the $\propto$ symbol means "proportional to", that is, if one increases by a certain factor, so does the other. If $v$ doubles, then so does $t$, and vice versa, so plotting one against the other gives a straight line. Comparing the $v - t$ and $L - t^2$ relationships, it must additionally be true that $v \propto \sqrt{L}$, so plotting $v$ (y axis) versus $\sqrt{L}$ (x axis) should give a straight line. Note that this implies that if we increase $L$ by a factor of 4, $v$ increases by only a factor of 2 - so to double the our speed, we need four times the distance to fall or roll.

- Make a new column that has $\sqrt{L}$. In Excel or Google Sheets, use the function "sqrt( )".
- Plot $v$ (y axis) versus $\sqrt{L}$ (x axis)
- Add a linear trend line, and if you know how, set the intercept to zero (covering zero length should take zero speed). How good is the fit, qualitatively?

## 4.4 Acceleration

Finally, if the acceleration is really constant, we should just calculate it. The average acceleration would be the average speed divided by time. Since the average speed is already distance divided by time, basically we are dividing the distance by the time twice, or $a = v/t = (L/t)/t = L/t^2$.

- Make a new column that calculates $v/t$ at each time $t$.
- Find the average of all your $v/t$ values and record this value.
- Make another new column that divides each $v/t$ value by the average value and subtracts one ($\frac{v}{t} - 1$). Multiplied by 100, this is your percent error (or just ask Excel/Google Sheets to display that column as percentages). What is the second-to-largest error you observe?

## 4.5 Conclusion

**Overall, considering all three methods of analysis, do you think the hypothesis of constant acceleration is supported?** Explain. (For this experiment, you can take our experimental uncertainty as around 10%.)

## 5 Things to (minimally) include in your Report

- Things which are in combinations of meters and seconds, not centimeters or millimeters. Inches and feet are right out.
- Include your raw $t$-$L$ data and calculations for all the requested quantities above.
- Include plots of $t^2$ vs $L$, $v$ vs $t$, and $v$ vs $\sqrt{L}$ and calculations required to produce them (e.g., Excel sheet). Make sure the plots have trendlines (linear).
- Include your $v/t$ calculations and the percent error.
- Include your conclusion as to whether the hypothesis is supported or not.

## 6 Format of Report

Your report need not be formal, the format is largely up to you. A single Excel/Google Sheets file is fine if well-organized and labeled, as is e.g., a Word document with graphs/sheets included. Handwritten reports and graphs are also fine. Whatever you are most comfortable with is fine, so long as all the requested information is present and easy to find.