Lab 0

Measuring Distance and Time

Physical Models: Sphere, Equivalence Principle

Analysis Tools: Mean, Standard Deviation, Standard Deviation of the Mean, Measurement Precision

Experimental Systems: Marbles of various colors and shapes

Equipment: Caliper, Micrometer, Tape Measure, Stopwatch

Safety Concerns: None, but please keep track of the marbles so none end up lost on the floor.

Introduction

Each week in lab this semester you'll be designing and conducting experiments to investigate how well various physical theories and concepts from General Physics I apply to real world systems. Although we'll supply you with physical models to test, experimental systems to explore, and analysis tools and equipment to utilize, you'll be given some freedom in how you approach each investigation. We hope this freedom will make the course more interesting. Research also suggests it's a significantly better way to learn experimental physics than following cookbook style instructions. Most importantly, *this is how science actually works.* [1]

This first lab will be a lot more structured than usual in order to prepare you for future labs. We'll still give you some choices to make, but the emphasis will be on rigorous analysis. You will find that providing scientifically sound answers to even *very "simple"* questions can require careful thought and some effort.

In the end you'll turn in lab notes like you will for future labs. As you go through the lab make sure to record answers to underlined instructions.

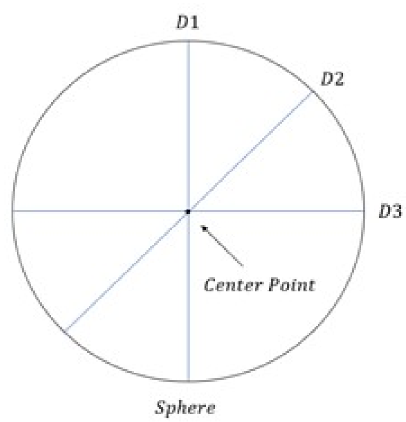
[1]Holmes and Wieman, "Introductory Physics Labs: We Can Do better", Physics Today January 2018

Part 1. Geometry and Precision Measurement

Attempts to understand the physical world have been ongoing since prehistory. Arguably the first physical theories to be genuinely scientific in the sense of being *mathematically precise* and *empirically validated* were theories of geometry. Euclidean Geometry describes our world to high [2] accuracy and even ancient people relied on geometric concepts to determine distances, to allocate plots of land equally, and for navigation and warfare.

So we'll likewise begin our investigations with geometry. We will ask a seemingly simple question: is a given object a sphere? But we will aim to be mathematically precise and to approach our investigation with appropriate empirical practices. What does this mean?

First we need to be explicit about what we mean when we say something is a sphere or not. A sphere is the set of all points equidistant from a given (central) point. This means any straight line passing through the center should have the same length. As in this picture:



A quantitative test we can perform to check if something is indeed a sphere is just to measure a collection of diameters and see if they're the same or not. That is, we can check if:

$$D1 = D2 = D3... \tag{1}$$

The sphere is a "**Physical Model**". We want to investigate if it accurately describes some aspect of the world. For that we'll need an object to compare it with, an "**Experimental System**". Go to the front of the room and collect a few multi-color marbles of different colors, and another marble of your choice from the large bin.

Quick Check: Let's make a first attempt to check if one of these objects is a sphere using a simple measuring device. Undoubtedly it "looks" like a sphere, but we must be quantitative. Pick one of the marbles and use the tape measure to determine a single diameter.

Immediately, we encounter an issue. The tape measure is not infinitely precise! And it's a bit difficult to use with the marble. This means there will be some uncertainty related to our measurement. In the Prelab Activity we explained that an analog measurement generally has an uncertainty of at least 1/2 the smallest

[2] But actually not infinite!

increment. It may be more than this based on your ability to use the instrument effectively in any given case. Record a measurement for the diameter:

$$\textit{best estimate} \quad \pm \quad \textit{uncertainty} \quad (\textit{units}) \tag{2}$$

Now try this for a couple other orientations of the marble. You can mark spots with the dry erase pen to keep track. Does the marble appear to be spherical? This will require you to compare distinct measurements, each having an uncertainty. We'll learn more about the appropriate way to do this next week, for now you can simply conclude that it is spherical if all of the diameter measurements agree within the uncertainty. This will serve as your prediction for Part 1.

This procedure works as a first attempt. But you likely noticed it's hard to measure the marble diameter using the tape measure and the uncertainty is not especially small. We can do a lot better!

Designing Your Experiment: We'll treat the results of your "quick check" as motivation for a working hypothesis and a more rigorous investigation. Let's perform the experiment again but with some better equipment and more diameters. Also, let's check 3 marbles this time, two of different colors and the "extra" marble you got from the bin.

Extra Guidance

You'll have some freedom in how you approach this. Here are some choices you need to make:

- On your table you have two pieces of equipment and a cheat sheet that explains how to use both. Both are capable of measuring distances more precisely than the tape measure. The Caliper is easier to use, while the Micrometer is harder to use but a little more precise. Both are large improvements over the tape measure. You may pick either one to use.
- You'll need to decide how many/which diameters to measure in each case. This is up to you, you just need to be explicit. And be explicit about the source of uncertainty: is it systematic, random, or both?
- You'll need to decide whether or not random or systematic uncertainty is larger in your experiment. To do this, you should measure the *same diameter* multiple times with the same device to see if there's small random differences each time you measure. Then decide if these random differences amount to an uncertainty larger than the precision of the device.

Check in with Another Group: Briefly discuss your plans with another group. They may provide you with additional ideas and feedback. Note one similarity and one difference between your approaches.

Conducting Your Experiment: Go ahead and give it a shot. You can change your method around while you're at it, you don't need to treat your previous decisions as a contract. Just make sure to record any changes for sake of your eventual final write-up. Make sure all of your data is labeled clearly with units, and that you keep track of uncertainty.

Forming a Conclusion: Does your data support the model that the marbles are spheres? Does it support it for some of the marbles but not others? Record a precise statement by citing your data, qualify it by citing your uncertainty, and discuss it in relation to your hypothesis.

Check in with Another Group: Check back in with the same group you discussed things with before. How do your results compare? Note two similarities and/or differences between what you found, and use this to inform your proposals for future iterations.

Forming a Conclusion Continued:Congrats on completing your first investigation. But science is an infinite enterprise, there's always more we can do. Based on what you found in this Part 1 decide on multiple (at least 3) possibilities for a next iteration of the experiment. (You don't need to actually do them)

A Final Question:You likely found that, given the increased precision, at least one of your marbles wasn't a sphere. But is it totally wrong to describe the marbles as spherical? Should we sue the manufacturer? Answer by referencing your results.

Part 2. Rolling Time and Statistical Uncertainty

Equally fundamental to physics are measurements of *time*. Even in ancient times it was important to be able to predict the seasons and determine the time of day, and much effort went into precision measurements of the orbital periods of the moon and planets. So let's proceed with a precision measurement of time.

Although it took much longer than the examples mentioned above, it was eventually recognized that all objects fall at the same rate, regardless of what they're made of. The modern version of this idea is called *The Equivalence Principle*. Unfortunately it's somewhat difficult to measure the time it takes for e.g. a marble to free fall to the ground because it's so quick. Early researchers like Galileo Galilei recognized we could perform an analogous measurement by rolling things down a ramp.

Let's conduct a related experiment. We will ask: does the time it takes a marble to roll down a ramp depend on color? On which marble we're using?

Quick Check:Configure your wooden ramp so that it's inclined (at any angle you choose). You may also want to place a meterstick at the end of the ramp to block the marble from rolling off the table.
Pick one of the multi-color marbles and measure the time it takes for it to roll down the ramp from some fixed location. Do one trial and record the result and the (systematic) uncertainty.

List all of the influences that go into determining the time it takes for the marble to roll down the ramp based on what you observed and what you know. Is there any reason to think the time should depend on color? This will serve as your prediction for Part 2.

Now do a trial with another, differently colored, multi-color marble.

Likely you did not get the same result both times, even taking into account the limits on the precision of the stopwatch. Does this establish whether or not rolling time depends on color?

Certainly not. We need to take into account the many random influences and differences that occur each time we drop the marble down the ramp. That is: we need to account for statistical uncertainty. Using the statistical methods your TA went over at the beginning of class.

Designing Your Experiment: Design an experiment to test if the two differently colored marbles, and the extra marble, roll at different rates. Make sure to record your method. Plan to do enough trials so that the uncertainty is as low or lower than the precision of the stopwatch. Be explicit about the source of uncertainty: is it systematic, random, or both? Which of these does taking additional measurements reduce?

Check in with Another Group: Briefly discuss your plans with another group. They may provide you with additional ideas and feedback. Note one similarity and one difference between your approaches.

Conducting Your Experiment: Just like in Part 1!

Check in with Another Group: Check back in with the same group you discussed things with before. How do your results compare? Note two similarities and/or differences between what you found, and use this to inform your proposals for future iterations.

Forming a Conclusion: Did you find differences between the marbles? Did color matter? Did the 3rd marble behave differently? Write down a quantitative assessment, including uncertainty. As before, also write down a few ways you could improve the experiment.

Organizing Your Lab Notes for Submission

If you've recorded everything as directed in the underlined portions of the manual, you have everything you need for the lab write-up. In this class we (typically) won't have you write formal lab reports, rather you'll write up your lab notes in an organized way. In the future you'll have an official rubric to follow. For today refer to the guidelines below for an explanation of what to include. You can also find a rubric on the Canvas page.

For both Part 1 and Part 2 you should make sure you've explained your methods clearly:

- Your goal is explained and includes a prediction (the predictions come from each "Quick Check")
- Your choice of measuring devices is indicated and there's an explanation of why you chose them
- Your use of any statistical and analysis tools is indicated and justified
- Your choice of variables to vary and measure, and how many data points you collected, is indicated

For both parts you should also have clearly presented data:

- Data should be presented in appropriate tables and/or graphs with units, labels, and titles
- Make sure your data fits with your proposed method
- Uncertainty should be evaluated/estimated appropriately and sufficiently minimized
- Double check that any analysis is performed correctly and in accordance with method

And for both parts you should have conclusions which include:

- A summary of your analysis and conclusions
- Quantitative results which support the conclusions
- Uncertainties and/or the limits of the experiment
- Multiple actionable proposals for a next iteration of the experiment
- A comparison with any initial predictions and answers to any direct questions posed in the lab manual