Measuring Instruments

Purpose

To gain familiarity with some of the instruments used in making measurements in the physics laboratory and to provide practice on how uncertainties in laboratory measurements are analyzed, by determining the mass density of a cylinder as well as the uncertainty in that density.

Pre-Lab Exercises

Before you come to lab:

1. Read the handout *Treatment of Data*.
2. Read through this entire handout. Make a spreadsheet table ahead of time, in which you can record your data during the lab.

⚠ *You should always read through the lab handout and prepare the necessary table(s) for recording your data before coming to lab.*

Introduction

Physics is an experimental science. The value of a theory is judged by how well it predicts or explains what we can measure. It is therefore necessary to define clearly what a measurement means. It is also incumbent on the experimentalist to conduct measurements in the most careful and competent manner possible. In this lab, we will put into practice the ideas set forth in the *Treatment of Data* handout. In particular, we will measure the mass density of a cylinder:

$$\rho = \frac{\text{mass}}{\text{volume}}$$

Analysis of uncertainty is a three-step process that consists of:

1. Estimating the unavoidable uncertainty in your experimental measurements.
2. Determining the resulting uncertainty in the calculated results using the rules of error propagation.
3. Using those final uncertainties to evaluate the significance of experimental discrepancies, if comparing to theory or to other measurements.

When performing your experiments in this course please keep the following in mind:

1. Estimates of uncertainty are just that, estimates. They are never guesses.
2. Genuine discrepancies (as opposed to blunders) between experiment and theory do occur even in student labs. These are generally due to real effects that have not been taken into account in the theory used to analyze the data. One of the most interesting and challenging aspects of data analysis is identifying possible reasons for such genuine discrepancies.

Usually at the end of an experiment we will compare our results with those of other methods or with the predictions of some theoretical calculation. This will involve comparing two or more values to see how well they agree with each other. Any difference between two such values is called a discrepancy. Keep in mind, however, that discrepancies are inevitable since the results of experimental work will always be subject to experimental uncertainty. The important question is, “Is the discrepancy within the limits set by the experimental uncertainty?” If it is, we say the discrepancy is not significant; that is, it is accounted for by the size of the experimental uncertainty. If the discrepancy is much outside the limits set by the experimental uncertainty, we say the discrepancy is significant; that is, it is not accounted for by the experimental uncertainty. (Please keep in mind that this is never an “all or nothing” judgment; significant discrepancies vary from somewhat significant to extremely significant.)

When the discrepancy is judged to be significant we have some more work to do. Without question, the first thing we must do is to check our calculations and make sure that we haven't simply made a mistake.

If our calculations are correct we should consider the possibility that we have underestimated the experimental uncertainties. Generally this can only be done by taking more data and reconsidering our estimates of the uncertainty in our measurements. If we find that we have underestimated the uncertainties, a reanalysis of the data may render the discrepancy insignificant.

Procedure

1. Make a table of values to be measured to calculate the density of a small cylinder. Measurements include diameter d, length l, and mass m. Be sure to also include a place for the uncertainties and fractional uncertainties.

   ⚠ *Many measured values should be converted to different units before further calculations and comparisons are performed. Be sure to include a place in your table to record the converted values.*

2. Do the following steps twice, once making measurements with the ruler and once making measurements with the vernier caliper.
   a. Measure the diameter d of your cylinder.
   b. Measure the length l of the cylinder.
   c. Determine the measurement uncertainty δd of the diameter of the cylinder.
   d. Determine the measurement uncertainty δl of the length of the cylinder.
   e. Calculate the fractional uncertainty $\delta d/d$ of the diameter measurement.
   f. Calculate the fractional uncertainty $\delta l/l$ of the length measurement.
3. From the fractional uncertainties of the diameter and length measurements, determine which device is more precise.
4. Calculate the volume V of your cylinder by using the most precise measurements from either the ruler or the vernier caliper. Remember, you measured the *diameter* of a cylinder, while the formula for volume uses the *radius* of a cylinder.
5. Do the following steps twice, once making measurements with the electronic scale and once making measurements with the analytic balance. Two-pan balances can be as precise as $1\ \mu\mathrm{g}$, but ours will be good to about $10\ \mathrm{mg}$ with the air currents in the room pushing it about.
   a. Measure the mass m of your cylinder.
   b. Determine the uncertainty δm of the mass of the cylinder.
   c. Calculate the fractional uncertainty $\delta m/m$ of the mass measurement.
6. From the fractional uncertainties of the mass measurement, determine which device is more precise.
7. Calculate the density ρ of the cylinder by using the *most* precise measurement from either the electronic scale or the analytic balance, and the volume that you calculated in step 4 above.
8. Calculate the uncertainty $\delta\rho$ in the density using the “Power Product Rule” for error propagation from the *Treatment of Data* document.

$$\delta\rho = |\rho|\sqrt{\left(\frac{\delta m}{m}\right)^2 + \left(-2\frac{\delta r}{r}\right)^2 + \left(-1\frac{\delta l}{l}\right)^2}$$

   ☑ *What is the relationship between the fractional uncertainty of the diameter to that of the radius?*

9. Now, calculate the density ρ and the uncertainty $\delta\rho$ in the density using the *least* precise of the four possible combinations: (1) ruler with electronic scale, (2) ruler with analytic balance, (3) caliper with electronic scale, or (4) caliper with analytic balance.
10. State your results in the form $\rho \pm \delta\rho$, expressed in standard SI units, with the correct number of significant figures.

⚠ *The correct number of significant figures is determined by the value of* $\delta\rho$*, as outlined in the* Treatment of Data *document.*

When you are finished with your analysis you should have a spreadsheet with all your data (diameter, length, and mass for each of the measuring instruments) clearly laid out and labeled, with units and measurement uncertainties indicated. The spreadsheet should perform all of the needed calculations and display the results (in this case, the density of the metal cylinder computed two times). If you do this, most of the post-lab quiz will consist of copying from your notes and spreadsheet.

Final Considerations

You should be able to address the following:

- Do your values for the density $\rho \pm \delta\rho$ agree (within the uncertainty) with the **accepted value of** $\boldsymbol{7620\ kg/m^3}$ for the two combinations of measuring instruments you used to calculate?