Lab 1

Meaningful Measurements

Experimental Objectives

- Determine the material of the objects by calculating their density and matching it to the accepted values for various common materials.

Introduction

Physics is a science which is based on precise measurements of the seven fundamental physical quantities, three of which are: time (in seconds), length (in meters) and mass (in kilograms); and all of these measurements have an experimental uncertainty associated with them. It is very important for the experimenter to estimate these experimental uncertainties for every measurement taken. There are three factors that must be taken into account when estimating the uncertainty of a measurement:

1. statistical variations in the measurements,
2. using one-half of the smallest division on the measurement instrument,
3. any mechanical motions of the apparatus.

Physicists study the physical relationships between these defined fundamental quantities and usually give a name to the newly derived physical quantity. These derived physical quantities have units which are combinations of the units of the fundamental ones. For example, the product of the lengths (in meters, m) of the three sides of a cube is called volume and has units of m^3. The ratio of mass to volume is called density and has units of $\frac{\mathrm{kg}}{\mathrm{m}^3}$. The concepts of volume and density are therefore derived from the fundamental physical quantities, rather than fundamental themselves.

1.1 Student Outcomes

In this exercise, students should learn how to to make precise and accurate length measurements with a meter stick and two types of calipers, how to read a vernier scale, and how to estimate uncertainty in a measurement. Students will make use of the relationship of the fundamental properties of mass and length to the derived concepts of volume and density.

1.2 Procedure

Materials: Three measuring devices: a metric ruler, a vernier caliper, and a micrometer caliper.
Several objects convenient for measuring the mass and the physical dimensions.
Procedure:

- Check the measuring devices for any **zero-point errors** (verify that they are **calibrated**). The use of the caliper and micrometer is outlined below.
- There are also several solids available: a cylinder, a cube, and a sphere.
  - Measure the dimensions of two of the objects with each of the three instruments: the ruler, the vernier caliper, and the micrometer caliper. Take all measurements minimizing any parallax errors.
  - Estimate the experimental uncertainties of your measurements. Do Exercises 1.2.1, 1.2.2, and 1.2.3.
  - Repeat the measurements at several positions and orientations around the object, compute the average and the relative uncertainty.
- As outlined in the Analysis, compute the volume and the density.

Exercise 1.2.1 (Zero-Point Errors)**.** You should verify the calibration of your instruments. Determine if there are the zero-point errors for each of the measuring instrument.

Hint. You might re-read the description of systematic error to remind yourself what a **zero-point error** is.

Hint. Is the meterstick rough on the end? Is the edge marked as zero actually at the zero value? Can you think of a way to ensure that the condition of the meterstick does not impact the measurement of length? How does the distance from zero to five compare to the distance from one to six?

Hint. Does the caliper read zero when it is measuring a zero length?
You should close the caliper to determine this.

Hint. Does the micrometer read zero when it is measuring a zero length?
You should close the micrometer to determine this.

Solution. You should figure out how to make efforts to correct for zero-point errors.

For each instrument, if the measurement you consider to have zero-length is not actually "zero", then you can handle that in the same way that you know the distance from 1 to 6 (in this case, subtract 1 from any measurement you make) or from 2 to 7 (in this case, subtract 2 from any measurement you make) or from 10 to 15 (in this case, subtract 10 from any measurement you make) .

You will also need to concern yourself with whether this uncertainty is **systematic** (always making the answer slightly too big or always slightly too small) or **random** (sometimes making the answer slightly too big and sometimes slightly too small). (Recall Subsection A.2.1.)

Exercise 1.2.2 (Parallax)**.** Determine if the value you are reading depends on the location of your eye.

Hint. For the caliper and the micrometer, the instrument clamps around the item being measured. Decide if the location of your eye matters in the measurement.

For the meterstick, you have to align the edge with a tick-mark. Does the location of your eye impact the alignment of the tick-mark on the ruler with the edge of the object?

Solution. You should figure out how to make efforts to correct any parallax errors. It may help to determine whether this uncertainty is **systematic** (always making the answer slightly too big or always slightly too small) or **random** (sometimes making the answer slightly too big and sometimes slightly too small). (Recall Subsection A.2.1.)

For each instrument, if the measurement does depend on the location of your eye, then you might try measuring it multiple times with your head in different locations each time to gauge the size of this uncertainty.

In the case of the meterstick, the object being measured should be as close as possible (touching?) the tick-marks of the meterstick in order to minimize parallax.

Exercise 1.2.3 (Random or Systematic)**.** When you measure the diameter of a sphere, it might be difficult to get the caliper precisely at the full diameter. If you are off, then you will necessarily be measuring a smaller value. This is a systematic error that can be corrected for. Since any mistake necessarily gives a value that is too small, then measuring it multiple times and finding the largest value will minimize this uncertainty.

On the other hand, if you measure an egg, you would not expect the diameter to be the same. Clearly for an egg, there is no reasonable single value to use as The Diameter. In this case, the question of finding the diameter does not make sense, and by measuring in a systematic pattern, you can determine that the shape is not spherical.

Determine if the zero-point error and the parallax error are random or systematic.

Hint. If a meterstick is worn down at the zero-value, then is it more likely to be measuring too short or too long? Is that systematic or random?

Hint. For a measurement affected by parallax, is that systematic or random?

Solution. Since random errors might give a result too big or too small, measuring many times and averaging should minimize these errors.

Since systematic errors tend to be either too big or too small (in a predictable or explainable way), you should track the uncertainties and recognize if this measurement causes your result to be more likely too big or more likely too small.

1.2.1 The Vernier Caliper

The vernier scale was invented by Pierre Vernier in 1631. This scale has the advantage of enabling the user to determine one additional significant figure of precision over that of a straight ruler.

For example, this eliminates the need for estimating to the tenth of a millimeter on the metric ruler. The vernier caliper, shown in Figure 1.2.4, can measure distances using three different parts of the caliper: outside diameters (large jaws), inside diameters (small jaws), and depths (probe). You should locate these three places on your caliper. The vernier device consists of the main scale and a movable vernier scale. The fraction of a millimeter can be read off the vernier scale by choosing the mark on the vernier scale which best aligns with a mark on the main scale.

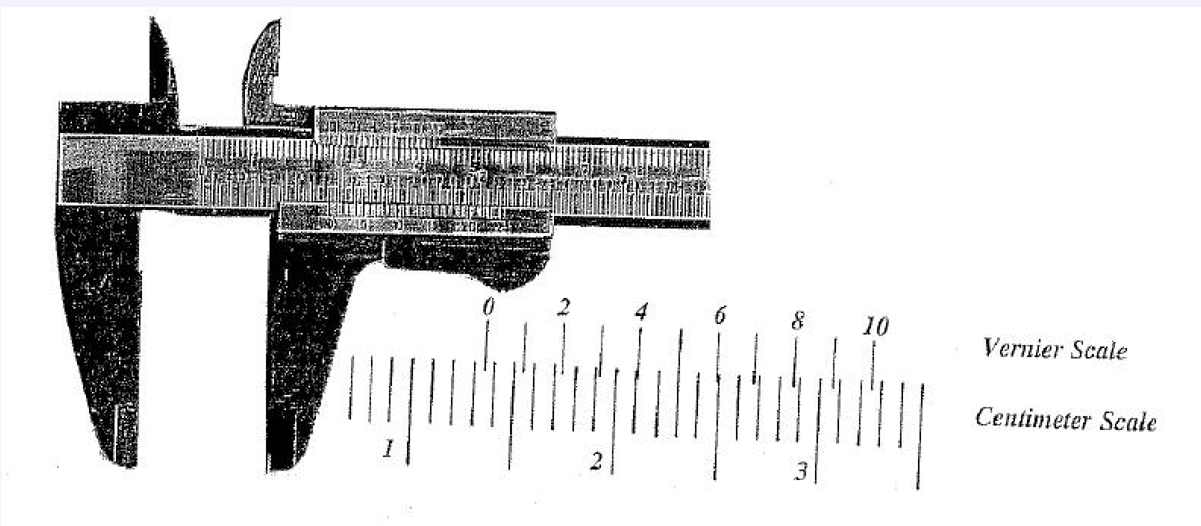

Figure 1.2.4: The location of the zero on the vernier scale tells you where to read the centimeter scale (1.3 cm). The vernier-scale line that lines up tells you the next digit (5). This picture measures $1.35 \pm 0.01\,\mathrm{cm}$ because we can distinguish 1.35 from 1.34 and 1.36, but we cannot gauge the result any more precisely.

To move the vernier scale relative to the main scale press down on the thumb-lock, this releases the lock and then move the vernier scale. Do not try to move the vernier scale without releasing the lock.

1.2.2 The Micrometer Caliper

A micrometer caliper is shown in Figure 1.2.5. This instrument is used for the precise length measurement of a small object. The object is placed with care between the anvil and the rod. It is very important to not tighten down on the object with a vise-like grip. Tightening with force will **decalibrate** the micrometer (causing a zero-point error). The rotating cylinder moves the rod, opening or closing the rod onto the object. There is a rachet, at the far end, for taking up the slack distance between the anvil, the object and the rod, so again do not over-tighten with the rotating cylinder. The linear dimension of the object can be read from the scale.

Rotating the cylinder one revolution moves the rod 0.5 millimeters. The rotating cylinder has 50 marks on it. Read the mark on the rotating cylinder that aligns with the central line on the main scale.

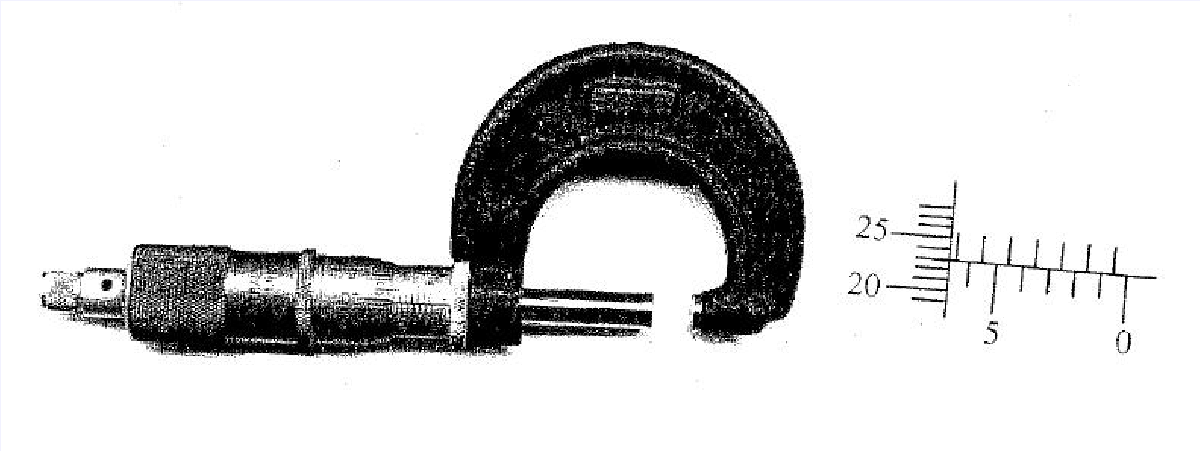

Figure 1.2.5: Notice on the coarse scale, that the lower lines read (1, 2, 3, ... 6 in this picture) and the higher lines read the half-marks (0.5, 1.5, 2.5, ... 6.5 in this picture). The location of the turning dial tells you where to read the coarse scale (6.5 mm). The center line of the coarse scale tells you where to read the fine scale. This is 23.0 (in units of $\times 10^{-2}$ mm), but not 23.5 and not 22.5 so the precision is 0.5 (in these units). This measurement in mm reads $6.5\,\text{mm} + 0.230\,\text{mm} = 6.730 \pm 0.005\,\text{mm}$. Since each mark corresponds to 0.01 mm and you can probably gauge a distance about half-way between the lines, the precision of this instrument is 0.005 mm.

The reading of the micrometer from Figure 1.2.5 is $6.730 \pm .005\,\text{mm}$.

1.3 Analysis

- After finding the relevant dimensions of the object, calculate the volume of the object three times: once using the measurements from the ruler, once from the caliper, and once with the micrometer.
- Using the rules of propagation of uncertainty, compute the uncertainty in the volume for each.

Exercise 1.3.1. Which instrument is the most precise?

Hint. For which instrument can you measure to the most decimal places?

- Measure the volume directly with the graduated cylinder.

Exercise 1.3.2. Are any of the volume measurements inconsistent? What can you infer about the accuracy of these instruments? Using the most precise indirect measurement of volume (those calculated from other measurements), calculate a percent-difference with the direct measurement of volume.

Hint. When you measure the volume of (let's say the cylinder) with a meterstick, with a caliper, with a micrometer, and with a graduated cylinder, they are all measuring the volume of the same object, which does not change volume. You *expect* these to all give the same number. The question is whether or not *your data* do actually give the "same" values.

Hint. Since you are using measurement techniques that have different precision, you will have different ranges of uncertainty. Numbers are considered to be "the same" when their uncertainty ranges overlap.

Hint. Keep in mind that "imprecise" means "a large range in the uncertainty", whereas "inaccurate" means "inconsistent with the true value". (You might not know the true value.)

- Measure the mass and then, using the overall most precise measurement of volume, compute the density with its uncertainty.
- Using your best density value, find the percent-error against the appropriate value given by the text, or the *Handbook of Physics & Chemistry*.
- Other considerations that might help with your analysis:

Exercise 1.3.3. What would be the best method to measure the volume of an irregularly shaped object? Why?

Hint. To answer this, it might help to think about *how* you would measure something that is irregularly shaped with each of the instruments you used today. Is one of them particularly good at conforming to the shape of an irregularly shaped object?

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A PDF version might be found at Measurement.pdf (291 kB)