

## Measurements in the Physics Lab: Basic

### Taking Data

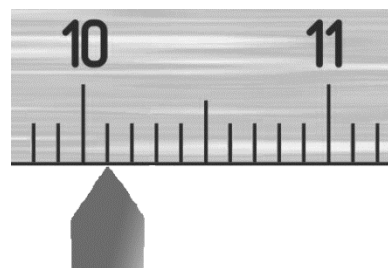
*How do you ensure the instruments give accurate readings?*

In principle, the instruments need to be calibrated before taking measurements. For simplicity, we will assume that this is already done, so that 1 cm read by a meter stick is really 1 cm, etc. (We assume that the expansion due to temperature is negligible.)

However, you do need to verify that the reading of the instrument starts at zero. If not, you should set it to zero, or record the “zero reading” and correct the final reading accordingly. For example, if we use a bathroom scale to measure mass, we should adjust the knob so it reads 0.0 kg with nothing on it. If for some reason that is not achieved and the scale reads 2.0 kg with nothing on it, then you must subtract 2.0 kg from all readings to get the correct mass. Note that if the zero reading is negative, then the corrected reading is larger than the actual reading (subtracting by a negative number).

*How many digits should I read when taking data?*

- For digital devices, read all the displayed digits. If a digit flashes so quickly that you cannot tell what it is, then don't record it.
- For analog devices, read until you have to estimate. Record one estimated digit, not two. If the pointer is right on a division line (see figure on the right), your estimated digit is 0. For example, the reading on the right should be 10.10.



*How do you report data?*

Use ink when recording data in the “Data” section of your lab report. When recording data, you must give the following:

- Explanations: explain what the data represents. Is it the length of a pencil? Mass of a cart?
- Units: use the unit of the measuring device.
- Uncertainties: see below for further explanation.

### Uncertainty

*What is uncertainty?*

All measurements are subject to some uncertainties: no matter how careful you are, you can never measure the “exact” value of a quantity. Instead, you determine the value within some range. A smaller range means the uncertainty is smaller and your measurement is more precise. For example, if you measure the length of a desk and report it as 2 m, you cannot mean that it is exactly 2.0000000... m. Depending on how carefully you made the measurement and what measuring instrument you used, you may mean that the length of the desk is between 1.8 m and 2.2 m, judging by eye. That means the “true” length may differ from 2 m by 0.2 m either way, or you should report the length as  $(2.0 \pm 0.2)$  m. Here, 0.2 m is the uncertainty of the length. If you use meter sticks and measure more carefully, you can reduce the uncertainty of the length but never eliminate it. Indeed, there are uncertainties even in the

measured values for universal constants used in cutting edge research. Specific research projects are set up to measure these values to less and less uncertainties.

A measurement is useless without an uncertainty. However, outside the laboratory context, you do see and use numbers without uncertainty: for example, your friend is 21 years old, 1.78 m tall, and weighs 70 kg. When you say so, you imply the uncertainty is in the last digit.

Uncertainty is often also called “error”. This does not mean that it is a mistake, but rather, it is a professional way of communicating your confidence level for the accuracy of the data.

### *Terminology*

For the measurement of a length  $L = (2.0 \pm 0.2) \text{ m } (\pm 10\%)$ ,

- 2.0 m is called the *value*, or the *best estimate* of the length.
- 0.2 m is the *uncertainty*, or *absolute uncertainty*, noted as  $\delta L$ . It has the same units as the value.
- 10% (calculated by  $\frac{\delta L}{L} \times 100\%$ ) is called the *percentage uncertainty*.

### *How do you decide on and report the uncertainty?*

Determining the uncertainty in a measurement is an “art” that is learned through experience and requires considering multiple possible sources. Clearly, the uncertainty depends on the measuring device. Moreover, the uncertainty also depends on what is being measured and how it is measured.

First, uncertainty is limited by the precision of the measuring device. Unless otherwise specified, we will use following in the lab:

- The precision of the digital devices is  $\pm 1$  in the last displayed digit.
- The precision of the analog devices is half of the smallest division.

Other factors aside from the measuring device are situation-dependent, and no hard rules can be given. When you take data, use your observations, common sense, and experience to decide the range of the possible values and thereafter decide the uncertainty. For example, say you measured the time it took you to cycle to Langara College to be 18.5 minutes, but despite your watch which can measure time to the nearest second, your experience tells you that 18 or 19 minutes are also possible. Then you would decide the uncertainty to be 0.5 minutes, which is half of the possible range.

When possible, repeating the measurement will help you to decide the range and the uncertainty. With repeated measurements, you can also consider the observed range of your measurements (scatter):  
$$\text{scatter} = (\text{largest measurement} - \text{smallest measurement})/2.$$

Of the above, you should pick the biggest. In your report, all raw data must have uncertainty.

#### **Deciding and recording the uncertainty**

The uncertainty should be the bigger of: (1) the precision of the measuring device; (2) half of the possible range, which is obtained either by estimation or by repeating the measurement.

## Significant Figures

*What are significant figures?*

“Significant figures” (sig figs) or “significant digits” are the digits that carry meanings. When taking readings, the sig figs are all the digits you are certain about plus the one digit you estimate. For example, to measure the height of your desk, you are certain that the height is between 76 and 77 cm, but you have to estimate the first decimal place since it could be either 0.3 cm or 0.4 cm. Therefore your reading is 76.3 cm and there are 3 sig figs. Do not record 76.35 cm unless you are certain about the digit “3”.

In most cases, the last sig fig and the uncertainty are at the same decimal place, and that is where you stop recording the data. But readings from digital devices or computer software may contain digits that are not sig figs or not meaningful. For example, if you measure a time using a stopwatch, the display shows 9.23 s; however, the uncertainty of this reading can be 0.18 s, which means you are uncertainty at the tenths place “2”, thus the digit at the hundredths place “3” is not meaningful. In other words, only digits “9” and “2” are significant. We can record this as  $(9.\underline{23} \pm 0.18)$  s to remind us that there are 2 sig figs instead of 3. (Uncertainty 0.18 s was decided by starting and stopping the stopwatch as quickly as possible.)

*How do you decide the number of sig figs in a measured data?*

For all cases, the last sig fig is at the decimal place where the uncertainty kicks in. Keeping this in mind, you first locate the last sig fig in a number, and then all the digits to its left, except leading zeros, are sig figs. For example,  $(76.3 \pm 0.1)$  cm has 3 sig figs,  $(21.60 \pm 0.05)$  g has 4 sig figs,  $(0.9 \pm 0.1)$  N has 1 sig fig,  $(19.23 \pm 0.18)$  s has 3 sig figs, and  $(0.83 \pm 0.18)$  s has 1 sig fig. If uncertainty is not given, we assume the uncertainty is in the last digit, so 1.08 m and 2.00 kg both have 3 sig figs.

*How do you decide the sig figs in a calculated result?*

While there are ways to calculate the uncertainty of a result and decide the sig figs accordingly, in this course we do not do so. We will determine the sig figs in the result using sig figs rules. There are two rules: (1) The multiplication or division rule is based on the number of sig figs, and (2) The addition or subtraction rule is based on the decimal places.

### **Multiplication or division rule**

The result has the same number of significant figures as the original data with the least number of significant figures.

The above rule leads to the following steps:

1. Finish the multiplication and/or division to get a result. Keep extra digits for now.
2. Count the number of sig figs in all the numbers involved in the multiplication/division. Choose the smallest one: This is the number of sig figs of the result. Mark the last sig fig of the result with an underline.
3. Round the result to its last sig fig. (Do this step only if it is the final result.)

Examples (the last sig fig is underlined for intermediate numbers):

$$7.8 \times 12.36 = 9\text{6}.408 \approx 96. \text{ (2 s.f. and 4 s.f, end up to be 2 s.f.)}$$

$$\frac{6.8 \times 10.37 \times 36.3}{4.222} = 6\text{0}.28 \approx 6.1 \times 10^2$$

(2 s.f., 4 s.f, 3 s.f. and 3 s.f., end up to be 2 s.f.)

#### **Addition or subtraction rule**

The result has the same number of decimal places as the original data with the least number of decimal places.

The above rule leads to the following steps:

1. Finish the addition and/or subtraction to get a result. Keep extra digits for now.
2. Count the number of decimal places in all the numbers involved. Choose the smallest one: This is the number of decimal places of the result. Mark the last sig fig of the result with an underline.
3. Round the result to its last sig fig. (Do this step only if it is the final result.)

Examples (the last sig fig is underlined for intermediate numbers):

$$7.8 + 2.4 = 10.2 \text{ (1 decimal place and 1 decimal place, end up to be 1 decimal place.)}$$

$$7.8 + 12.24 = 20.\text{0}4 \approx 20.0 \text{ (1 decimal place and 2 decimal places, end up to be 1 decimal place.)}$$

$$7.302 + 3.14 - 2.3 = 8.\text{1}42 \approx 8.1 \text{ (3, 2 and 1 decimal places, end up to be 1 decimal place.)}$$

$$2.4 \times 10^5 + 29 = 2\text{4}0000 + 2\text{9} = 2\text{4}0029 = 2.\text{4}0029 \times 10^5 \approx 2.4 \times 10^5$$

(For numbers without decimal point, the decimal place is where their last sig fig is. 240000 has a decimal place of ten thousands and 29 has a decimal place of ones. The result will follow the *left-most* decimal place.)

For mixed calculations, calculate step by step and apply the appropriate rule in each step:

$$\frac{10.723 - 9.9}{0.202} = \frac{0.\text{8}23}{0.20\text{2}} = \text{4}.0743 = 4.$$

(The result of the subtraction should have 1 decimal place so it is 0.823. Then, for the division, 1 s.f. and 3 s.f. end up to be 1 s.f. The decimal point at the very end differentiate it from an integer 4)

You may have noticed that in the example calculations, we began by writing the result with a few extra digits—usually 5 or more non-zero ones—and then wrote the result to contain only the sig figs. The reason for this is that you may want to use the result for further calculations. We must keep extra digits for the intermediate numbers to avoid *rounding errors*. However, your final result must contain only the sig figs without any underlines.