Physics Lab Preparation and Other Basics

(Theories and conventions for measurements and data analyses)

Introduction

Physics is one of the most quantitative sciences. It is important to obtain an experimental result as accurately as possible. This philosophy has contributed to the foundation of technologies and it enables us to make smaller engineering devices with quite a few functions. On the other hand, physics experiments have another objective to confirm or to falsify the correspondent theoretical prediction. We could never obtain the absolutely "true" value; however, it is significant for physics experiments to estimate the scientific tendency, such as how it approaches the expected value or how the data consistently indicate a rule or law.

The actual experimental procedure can be illustrated as follows: First, experimental data have to have objective properties; thus, we use units to express the experimental values to be comparable. Second, measurement always contains uncertainty, which is based on the limitation of the device capability and internal / external noise. Therefore, the last digits fluctuate and this gives us the meaningfulness of significant figures. This consideration can never be excluded as a scientific aspect, which leads to the error analysis. Third, only a few trials would not explain the inclination of data; hence, sufficient amounts of data have to be taken to support the result in terms of the statistical sense. The average and standard deviation of experimental data provide a major property of the experimental result.

From the various perspectives, the experiment can be improved to find more accurate results and to discover new scientific phenomena. This lab will procure the fundamental information on how you conduct physics experiments using analytical methods and various interpretations of your experimental data.

Objectives:

- To learn importance of physical units
- To learn experimental uncertainty and its analysis
- To learn how to acquire experimental data and how to process and interpret the set of data

1. Units and their importance

- <u>SI Units</u>
  The term, SI, derived from "Le Systeme International d'Unites", which means the international unit system in French.

  Attention! You now have to remember the three basic SI units, <u>meters (m)</u> for length, <u>kilograms (kg)</u> for mass, and <u>seconds (s)</u> for time.

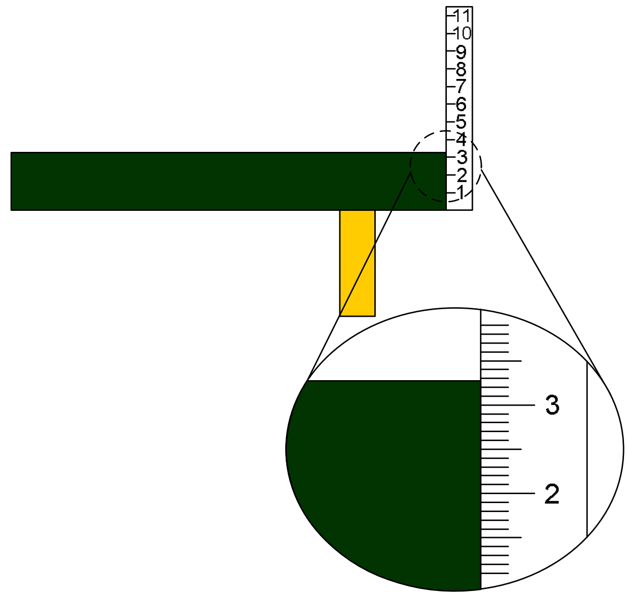
- <u>Why do we have to use units?</u>
  The main reasons are to compare the physical values and to confirm the consistency of the physical system.

  You may mention the mass is 100, but it can be 100 kg, 100 g, or 100 mg. Thus, a number without units has no meaning and it does not allow you to compare the values.

  A physical system is consistent, and so is the unit system since it is closely related. This is called dimension analysis. The units for physics or kinematics are consistent with the formulas. For example, velocity has the unit, m/s. Velocity is defined as length divided by time. The length has the unit, m, and time has s, so the unit and its formula are consistent in terms of this analysis.

- <u>Unit conversion</u>
  Sometimes, a physical value is given by non-SI units, such as 200 g. The value must be converted to be used in physics. One kilogram is equivalent with one thousand grams (1 kg = 1,000 g). The unit, kg, is a larger scale than "g." Thus, to convert it, you divide it by 1000. Namely, (200 ÷ 1000) = 0.200 kg. [Analogously, when 20 cents have to be converted into dollars, you will divide it by 100, not multiplying.]

2. Uncertainty and significant figures you have to obtain



- <u>Experimental measurement and uncertainty</u>
  Suppose you measure a length of the thickness of a table with a ruler. You may encounter the following situation: ① In the first look, the thickness reads a little more than 3 cm (0.03 m). ② When you look with more precision, it reads a little more than 3.2 cm (0.032 m).

  You may read as many figures as the tool of measurement provides. This ruler provides you to estimate one more digit, such as 3.27 cm (0.0327 m). The last digit "7" contains uncertainty. Under this measurement, you are able to obtain three digits (3, 2, and 7). These are called **<u>significant figures</u>**. You can say, this has three significant figures.

Attention! You always have to obtain one more digit than the measurer can indicate, which can be doubtful, but important to include.

Attention! According to the above discussion, the experimental values always take uncertain figure because no one obtains the "true" value of the physical quantity.

- <u>Why do we have to consider "significant figures" in physics?</u>
  For example, the mass of a water melon is told as 1.7 kg (2 sig.fig.), and another one is told as 1.73 kg (3 sig. fig.) *scientifically*. Which water melon is heavier? For the first one, the last digit of "7" of 1.7 kg is uncertain, so value ranges from 1.65 kg to 1.74 kg. The first water melon can be heavier if it has another digit like 1.74 kg. If not, it cannot be compared exactly in accordance because of the difference between the number of significant figures in each measurement.

3. Calculation of the experimental values and its rounding numbers

Attention! Use the same unit system (usually SI units) to calculate physical values.

The basic rule of rounding is following: When the digit is more than or equal to 5, it will be rounded up. When it is less than 5, it will be rounded off. (*The official rule involves more details.*)

- Addition and subtraction
  You have two physical values to be added, 3.67 and 1.3. The result will be
  $$3.6\underline{7} + 1.\underline{3} = 4.\underline{97} \Rightarrow 5.0$$
  The underlined digit(s) is (are) uncertain accordingly. Then, the last digit has to be rounded accordingly. Other examples are:
  $$2.3\underline{4} + 3.51\underline{6} = 5.8\underline{56} \Rightarrow 5.86$$
  and
  $$5.22\underline{3} - 0.45\underline{5} = 4.7\underline{68} \Rightarrow 4.77.$$

- Multiplication and division
  With the same procedure, we can calculate:
  $$3.5\underline{8} \times 0.2\underline{1} = 0.7518 \Rightarrow 0.75$$
  The final result is always fit with the least significant figures of calculated values. So is calculation for the division.

- Calculation with physical or mathematical constants
  For given reference values and constants, you have to use at least one more figure than the experimental significant number of figures. Suppose you calculate an area of circle. The radius of an object is 0.0262 m. The area will be πr^2. The radius has three significant figures, so π should be taken as 3.142 at least. (Note that you should use full figures of a constant if it is provided as reference.) The result is:
  $$\pi r^2 = 3.142 \times (0.0262\text{ m})^2 = 3.142 \times 0.000686 = 2.15\text{ m}^2$$

4. Types of error

- *The human error*?
  This error is just a *mistake*, and not a scientific estimate. You **MUST NOT** mention this sort of error in your report. Mistakes have to be corrected before you leave the lab.

> **Attention!** The human error can be caused by following: The experimenter does not grasp what is being measured. The skill to perform the experiment is not yet improved by the number of trials. (Make sure each time whether you obtain a proper result.) Simple calculation mistake also results in a wrong outcome.

- The random error
  This error is based on the capability of the device. It could have fluctuation toward the true value due to physical limits of the device. This error must be small enough to exclude any other major systematic errors and mistakes.

- The systematic error
  This error is induced by offset or zero setting mistakes. You may record the consistent results, but they are different from what you expect from the theory. It could be a simple mistake of how to read the result, how to set up the devices, or how you make the timing to measure. Also, some devices may have a problem which consistently causes wrong results.

  ☑ *When you encounter this sort of error, consult your instructor or try hints written in the manual.*

> **Attention!** You have to pay attention while you are measuring a physical value. Any one of the conditions could cause systematic errors. Think about where, when, how, and what for the experiment.

- The unanticipated external causes of error

The experiment can be formulated with a basic relationship. Besides the random and systematic errors, (absolutely, after you corrected any possible mistakes), suppose you still have some deviation, then it can be referred to as external effects toward the entire system, such as temperature, friction, pressure, time-dependent properties, and any other extra factors to be considered beyond the given formula. This is **worthwhile** to be discussed in your report.

5. Error analyses

- Percent error

  When there is a reference to be compared, the experimental value will be subtracted from it and divided by the reference (accepted) value, such as physical constants.

  Example

  The accepted value is 0.761 m and correspondent measured value is 0.782 m. Thus, the error will be calculated as

$$\frac{|\text{accepted} - \text{measured}|}{\text{accepted}} \times 100\% = \frac{|0.761 - 0.782|}{0.761} \times 100\% = 2.76\ \%$$

- Percent difference

  When the expected value is not known and one experimental value is not as important as the others, the error will be calculated with the difference between the values divided by the average value of them.

  Example

  The values you obtained are 2.87 kg and 2.76 kg under theoretically equivalent conditions, but with different ways. The error will be:

$$\frac{|\text{one} - \text{the other}|}{\text{these average}} \times 100\% = \frac{|2.87 - 2.76|}{\frac{1}{2}(2.87 + 2.76)} \times 100\% = 3.91\ \%$$

- Average (mean) and standard deviation

  The average value of the set of data is the likely index of the expected value. One calculates it as the sum of the data divided by the number of the trials. Let's calculate the average from the following set of data: 5.12, 5.43, 5.02, 5.72, and 5.31. Therefore, the average or mean value is (5.12 + 5.43 + 5.02 + 5.27 + 5.31) ÷ 5 = 5.23.

  Now, we can also think of another property of the set of data. Here is another set of data: 5.52, 5.15, 4.98, 5.49, and 5.01. The average is (5.52 + 5.15 + 4.98 +5.49 + 5.01) ÷ 5 = 5.23. Although the average is equal to the above two sets of data, the distributions of the values around the average are different. Namely, we should know how to quantify the difference. This is known as standard deviation.

  The standard deviation indicates how the set of data deviated from the average. Therefore, you subtract the average from each datum. Use the first set of data:

$$(\text{The } 1^{st} \text{ data, } 5.12 - \text{average, } 5.23)^2 = 0.0121$$
$$(\text{The } 2^{nd} \text{ data, } 5.43 - \text{average, } 5.23)^2 = 0.0400$$
$$(\text{The } 3^{rd} \text{ data, } 5.02 - \text{average, } 5.23)^2 = 0.0441$$
$$(\text{The } 4^{th} \text{ data, } 5.27 - \text{average, } 5.23)^2 = 0.00160$$
$$(\text{The } 5^{th} \text{ data, } 5.31 - \text{average, } 5.23)^2 = 0.00640$$

  The reason why it has to be squared is to avoid cancellation simply between positive and negative values. The sum of them is 0.0121 + 0.0400 + 0.0441 + 0.0016 + 0.0064 = 0.1042. This is divided by (the number of the trial – 1) [Note that this works even for small amount of the samples.] Thus, 0.1042 ÷ (5-1) = 0.02605. We square each deviation, so we eventually have to square root to get back the original, √ 0.02605 = 0.16. This is the ***standard deviation*** of the set of data. The general formula is given as

$$\text{STD} = \sqrt{\frac{1}{N-1}\sum(\text{Ave.} - \text{Each datum})^2}$$

where ∑ indicates the sum of each term. For the second set of data, we can do the same. The standard deviation is 0.26. Even though the data have the equal average, how it is distributed makes them different.

The scientific expressions of the above will be [average ± standard deviation]:

For the first set of data: 5.23 ± 0.16

For the second set of data: 5.23 ± 0.26

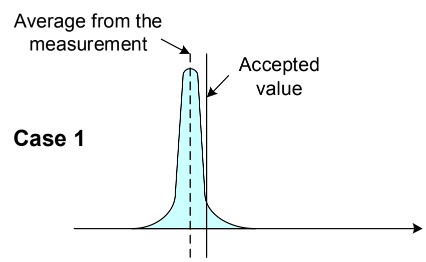
> **Attention!** You must understand and memorize the meanings of percent error, percent difference, and standard deviation because you will use these through the semester.

6. Interpretation of the experimental results

The average and standard deviation have to be written together to display the property of the set of the data as shown in the previous section. Namely,

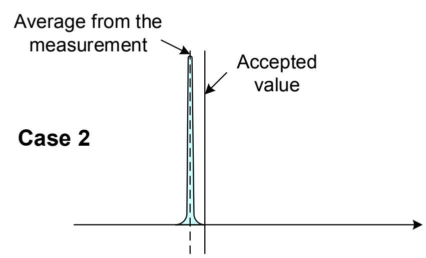
Average value ± standard deviation (units).

An accepted value of the speed of sound at room temperature is 343.2 m/s. Suppose your set of data gives the average and standard deviation as



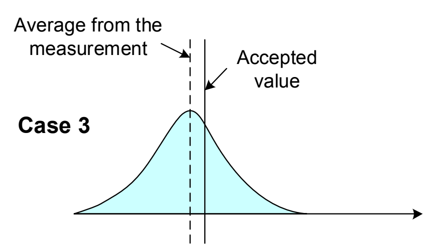
Case 1: 341.6 ± 2.4 m/s

This can be consistent and accepted as the final result since it is within the standard deviation to be agreed with the accepted value. Most of the standard deviation comes from the random error.



Case 2: 341.6 ± 0.12 m/s

The standard deviation is small enough to conclude that this is an accurate data. However, it does not fall on the accepted value. A possible reason can be referred to as a systematic error.



Case 3: 341.6 ± 12.56 m/s

This is consistent with the reference value; however, the standard deviation is too large. From this result, it is hard to identify the causes of error. The experimentation is possibly NOT suitable for obtaining the accepted value.

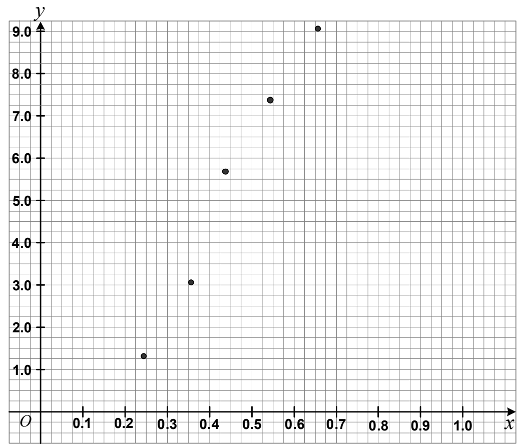
7. Data fitting with a slope

When a relationship between two variables is proportional linearly, the data should be analyzed by the slope. [Note: The systematic method to obtain the slope is called the least square fit.] Suppose you obtain the following relationship between two values.

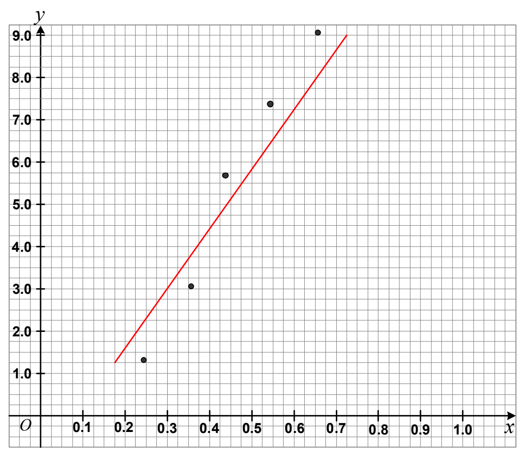
x	*y*
0.241	1.32
0.352	3.07

0.437	5.72
0.548	7.43
0.656	9.11

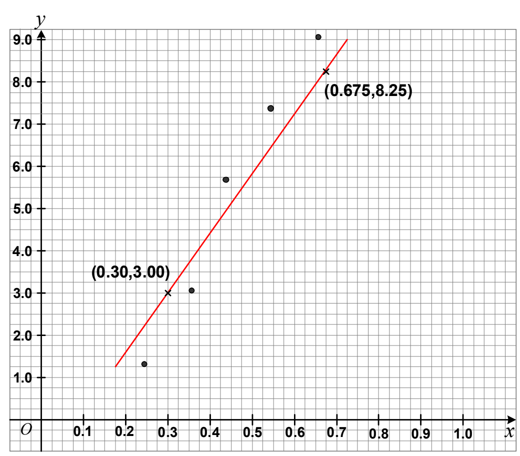
① Label the numbers with an equal space and plot the each point.



② Draw a linear line that is close to every point.



③ Pick out two points which can easily be read from the graph with an enough separation.

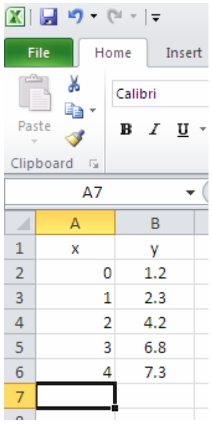


④ The slope is obtained by following:

$$\text{Slope} = \frac{y_1 - y_2}{x_1 - x_2} = \frac{8.25 - 3.00}{0.675 - 0.300} = 14.0$$

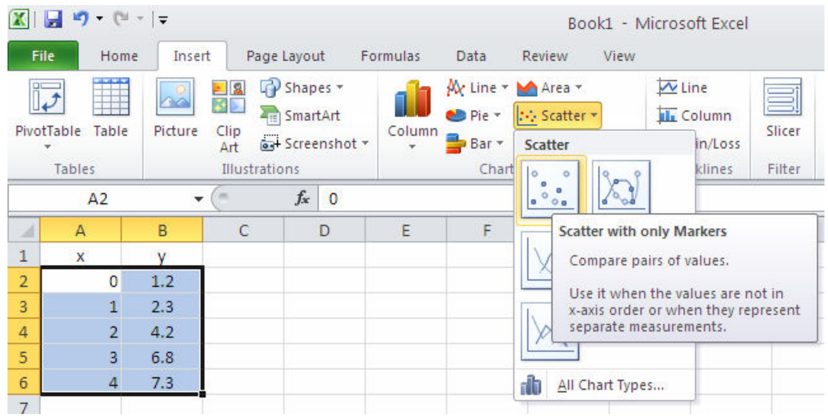
8. Slope acquisition with Excel spread sheets

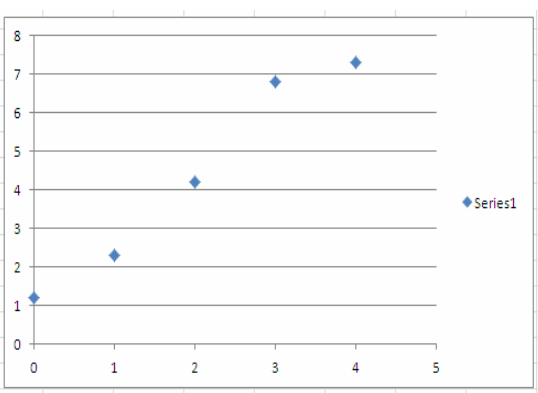
There is a systematic method to obtain the best fit line with a set of data. The name is known as least square fits. Here is an instruction of this method with Excel spread sheet.



① ⇦Type in the *x* and *y* values as follows:

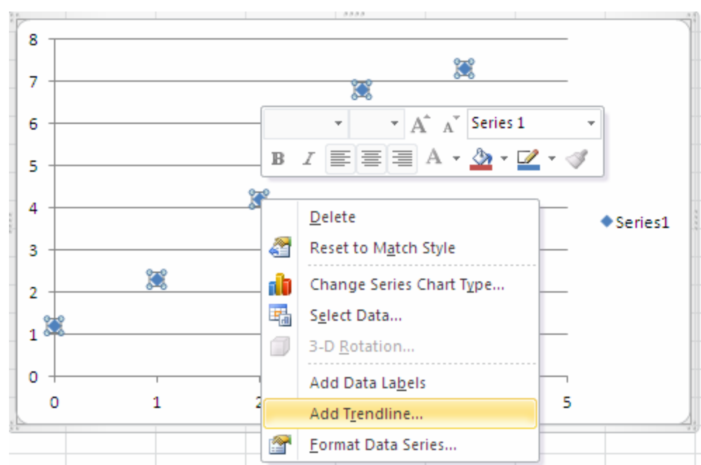
② ⇨Select the *x* and *y* values; click "Insert" tab to choose "Scatter."; and then, select "Scatter with only Markers."

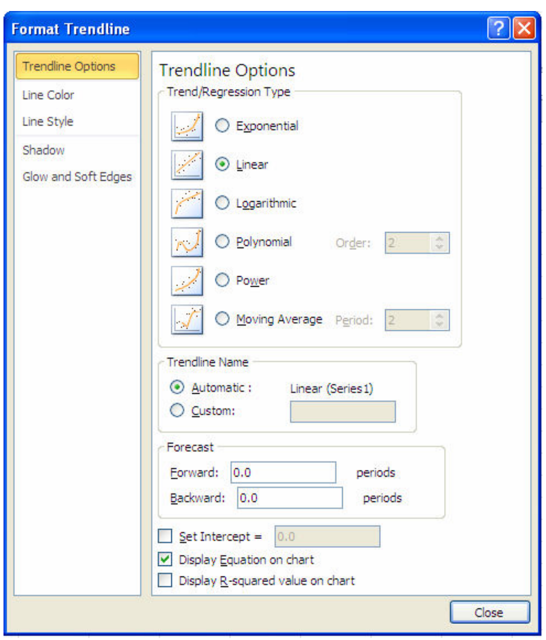




③ ⇦The plotted graph is popped up. Make sure it expresses the numbers you input.

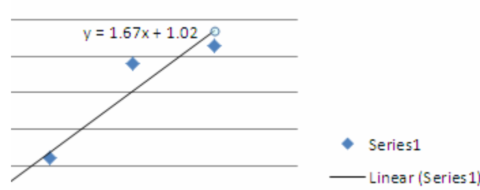
④ ⇨Right click 'exactly' on the plotted point. Any one of them works in the same way. Then, select "Add Trendline."





⑤ ⇦"Format Trendline" is popped up. Make sure "Linear" is selected, and check for "Display Equation on chart" at the bottom of this.

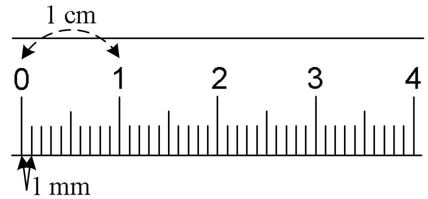
⑥ ⇨After closing the above, you will see the equation on the plot. The coefficient of *x* is the slope of the line.



9. Size and measurement

- Ruler

This is a typical ruler and the smallest calibration is 1 millimeter. Measure the length of following arrow and make sure with others.



_______________ (m)

_______________ (cm)

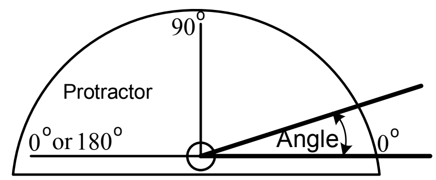
_______________ (mm)

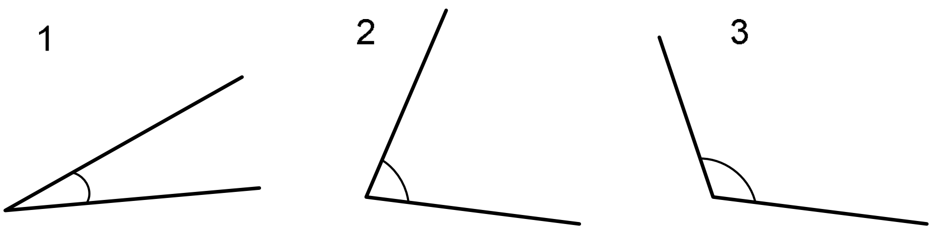
Conversion

1 cm = 10 mm
1m = 100 cm
1 m= 1000 mm

- Protractor

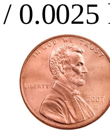
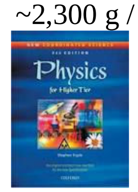
This is a tool to measure an angle. The smallest calibration is called a degree. To measure an angle, align one side with the "0° line" of the protractor as shown. The intersection of two lines has to be located at the center of a small circle as depicted. Measure the following angle with a protractor and make sure with others.





1. _______________ (degree / °)
2. _______________ (degree / °)
3. _______________ (degree / °)

This is the reference so you can compare your experimental results with some of typical lengths and masses.

<u>Typical LENGTHS of various objects</u>	**<u>Typical MASSES of various objects</u>**
The diameter of penny ~19.05 mm / 1.950 cm / 0.01905 m 	A penny ~ 2.500 g / 0.0025 kg 
The width of letter size of paper ~216 mm / 21.6 cm / 0.216 m	A baseball ~150 g / 0.150 kg 
The length of letter size of paper ~279 mm / 27.9 cm / 0.279 m 	A physics textbook ~2,300 g / 2.300 kg 
The height of a standard car ~1,500 mm / 150.0 cm / 1.500 m 	One gallon of water ~3,785 g / 3.785 kg 

Problem Sets As an Assignment

Your Name ____ ID ______________________

❶ Write down the SI units for mass, length, and time.

❷ Convert the following expressions into SI units. (Show your work.)

230 cm ⇨ ____ (   )

19 g ⇨ ____ (   )

48 km ⇨ ____ (   )

50.5 pounds ⇨ ____ (   )

3.67 miles ⇨ ____ (   )

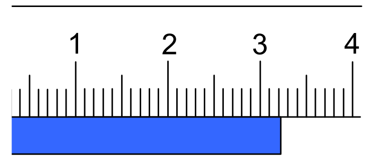
78.0 feet ⇨ ____ (   )

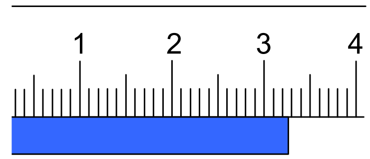
92.8 mg ⇨ ____ (   )

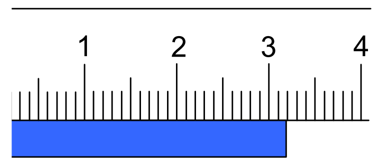
88.4 mm ⇨ ____ (   )

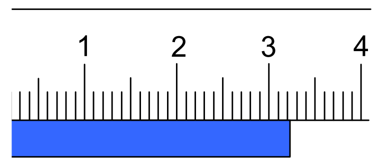
Unit Conversion Table
1 cm = 0.01 m
1 mm = 0.001 m
1 miles = 1609.344 m
1 kg = 1000 g
1 kg = 2.2046 pounds
1 m = 3.281 feet
1 mg = 10^{-6} kg

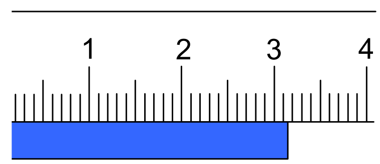
❸ The length of an object is measured by several people as follows: Read each with three significant figures. (**You must include an uncertain figure to be significant. Note that the ruler is a standard one explained in the previous section.**)











trial	Reading
1	
2	
3	
4	
5	

What is the average of this measurement?

____ (   )

What is the standard deviation (show the work)?

How many figures do you have to take? Explain the rule.

This is very important. From next lab, you have to follow this rule!

How would you describe the possible error for this measurement? Can it be a systematic error or a random error? Justify your answer.

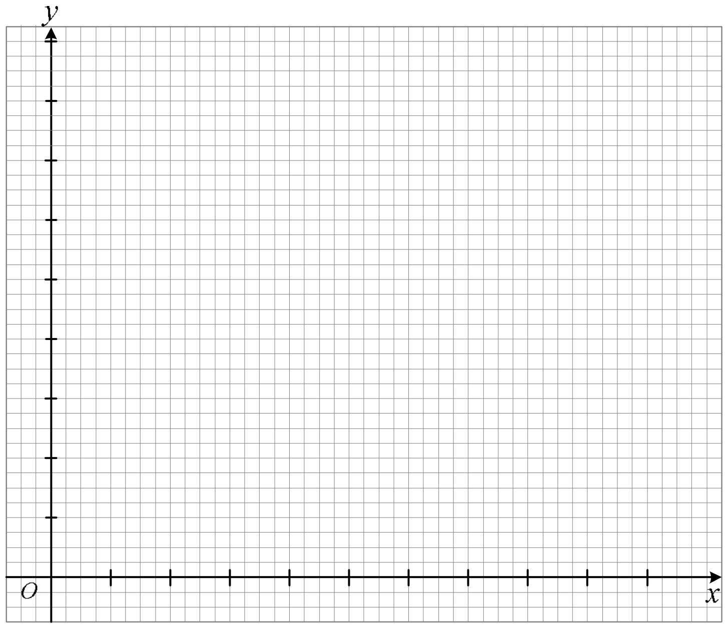
❹ You have obtained a velocity, 2.76 m/s. In the second trial, you obtained 2.65 m/s but the object has a different mass. What error analysis do you have to use to compare the two velocities (the percent error or percent difference)? Then, calculate it.

❺ From an experiment, you measured the average gravitational acceleration, 9.72 m/s^2. The accepted value is 9.82 m/s^2. What error analysis do you have to use for this (the percent error or percent difference)? Then, calculate it.

❻ Find the best fit slope out of the following data.

x	*y*
0.332	0.210
0.445	0.403
0.527	0.624
0.639	0.886
0.743	1.102

Follow the instruction in part 7 of this manual.



*You may want to do this again with the Excel spread sheet by following instruction 8.