General Physics Lab 1

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1 Introduction

"I hear and I forget, I see and I remember, I do and I understand" Confucius (Chinese Philosopher).

For example, you may learn about the concept of gravity by reading about it in a textbook or hearing your teacher lecture about it. However, you will not truly quantitatively understand gravity until you start conduct experiments related to it.

Physics is an experimental science in which theories are tested against observations. If theoretical predictions do not match the experimental results, then theories are revised. This process of experimentation and revision is how physics has advanced over the centuries.

1.1 Objectives of the Lab

- **Develop basic skills in experimental physics.** This includes learning how to use lab equipment safely and accurately, collect data, and analyze results.
- **Develop collaborative learning skills.** This includes working effectively with team members to communicate, share responsibilities, and solve problems.
- **Encourage independent intellectual discoveries.** This includes giving students opportunities to setup their own experiments, test their hypotheses, and learn from their mistakes.
- **Encourage curiosity to ask questions and determine methods and apparatus to answering them.** This includes fostering a spirit of inquiry and problem-solving in the lab.
- **Develop the ability to relate abstract concepts to observable quantities.** This includes helping students to see how the physical principles they learn in class are manifested in the real world.
- **Comprehend the role of observation in physics and to identify the difference between predictions based on theory and the outcomes of experiments.** This includes understanding how scientific knowledge is built through experimentation and how to distinguish between facts and interpretations.
- **Report on experiments and develop the necessary skills to communicate experiment findings in a scientific and concise way.** This includes writing clear and concise lab reports that communicate the experimental methods, results, and conclusions in a professional and scientific manner.

1.2 Lab Instructions

- **Prepare before coming to the lab.** Read the experiment thoroughly and understand the objectives, procedure, and safety precautions.
- **Use lab equipment with care.** Follow the instructions of your instructor.
- **Work collaboratively with your team members/partner.** Communicate effectively and share responsibilities.
- **Keep your lab space organized.** Clean up after yourself and put away all equipment when you are finished.
- **Always consult with your instructor before starting any experiment.** Get approval for your experimental setup and procedure.
- **Bring all necessary materials to the lab.** This includes a lab report template, graph paper, a sharp pencil, a ruler, and a calculator.
- **Have your data sheet signed by your instructor before leaving the lab.** This ensures that you have completed all of the required tasks and that your data is accurate.
- **Smoking, eating, drinking, and using cell phones are not allowed in the lab.** These activities can pose safety hazards and interfere with your work.
- **Plagiarism is strictly prohibited.** All work submitted for this lab must be your own. It is not accepted at all to copy any part of your report from others.

1.3 Lab Reports

- **Cover Page:** Make sure that the cover page is neat and professional. Include Title of the experiment, Date, Author(s) and Section .
- **Abstract:** Write the abstract after you have finished writing the rest of the lab report. This will help you to summarize the main points of the report concisely and accurately. Your abstract should include the aim of the experiment, the method used and the result. The result should be written in the correct format with the appropriate units (For example, if you measured the length of an object, you would write the result as $X \pm \Delta X = 4.43 \pm 0.06 cm$).
- **Theory:** Explain the relevant physical principles and concepts clearly and concisely. Use diagrams and illustrations to explain your experimental setup. Define all symbols used and explain how you combined the uncertainties.
- **Procedure:** Use step-by-step instructions and diagrams as needed to explain the steps of the experiment. Use simple past or passive voice.
- **Data:** Present the data in appropriate tables and figures to visualize the data, as needed. Write your data with

the appropriate significant figures and units. Be sure to sign your data before leaving the lab.

- **Calculations:** Show how the data was analyzed to produce the conclusions. Use graphs, mathematical equations and formulas to explain your calculations.
- **Conclusion:** Summarize the main findings of the experiment and discuss whether your results are consistent with accepted values. Address any errors in the experiment and suggest ways to improve the results when repeating the experiment.

2 Measurements and Uncertainties

A measurement of a physical quantity will never represent its true value with infinite precision. This is because there are always sources of error in any experiment. Sources of error in physics experiments can be classified into Random and systematic errors. Common sources of error in physics experiments include:

- Choice of Instruments (its precision, calibration, etc.. . .). For example, if a ruler with a millimeter scale is used to measure the length of an object that is 10 centimeters long, the measurement will be less accurate than if a ruler with a centimeter scale is used.
- Environment (temperature fluctuations, gravity, background radiation, etc..).
- The way in which an experiment is performed can also introduce errors. For example, if the experimenter does not follow the procedure correctly, this can lead to inaccurate results.
- Experimenter or Human error can also be a source of error in physics experiments. For example, the experimenter might misread a measurement or make a mistake in calculations.
- The way the physical quantity is measured.

2.1 Types of errors

2.1.1 Random errors

These are errors that occur randomly in experimental measurements and are caused by unknown and unpredictable changes. Such changes may occur due to the measuring instruments or in the environmental conditions. Examples of causes of random errors are:

- electronic noise in the circuit of an electrical instrument.
- irregular changes in outdoor temperature due to changes in the wind.

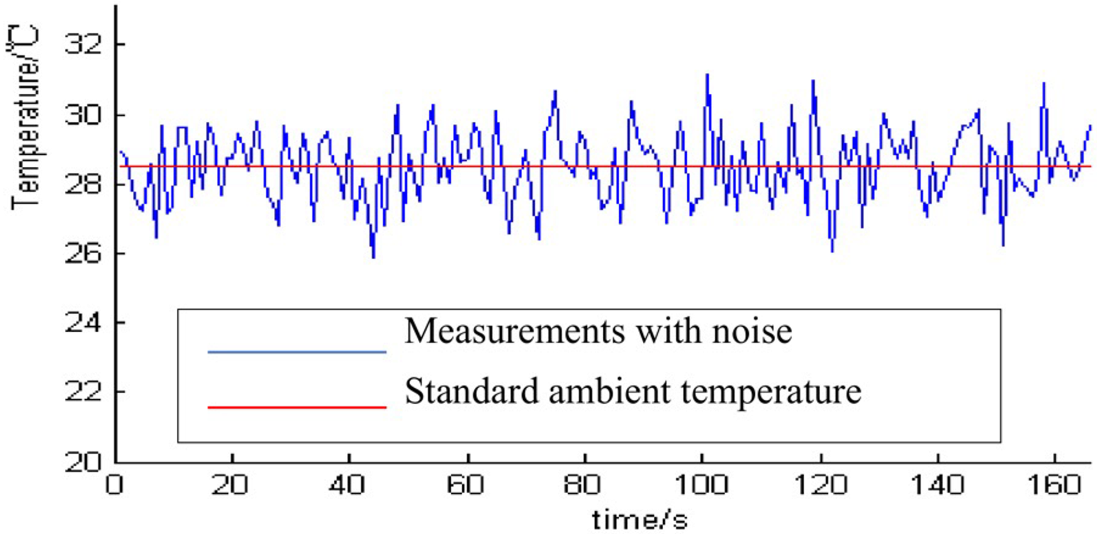

Figure 1: Temperature measurement as a function of time.

Best Estimate of the True Value: If $X_1, X_2, \cdots, X_N$ are measurements of a physical quantity, then the best estimate of the true value is the average value defined as:

$$\bar{X} = \frac{1}{N}\sum_{n=1}^{N} x_n$$

A measure of the uncertainty can be obtained from the sample standard deviation

$$\sigma_s = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}\left(X_n - \bar{X}\right)^2}$$

Uncertainty in the mean is defined as

$$\Delta\bar{X} = \sigma_m = \frac{\sigma_s}{\sqrt{N}}$$

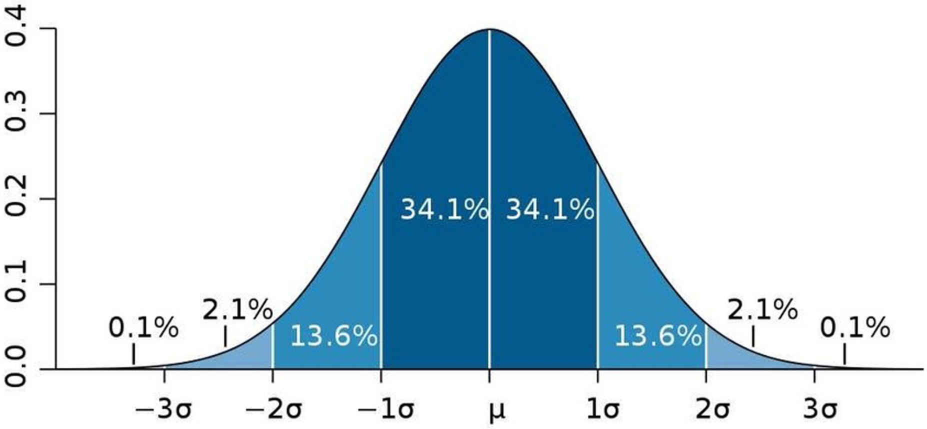

Figure 2: Normal distribution.

Note. The percentage of measurements between $\bar{x} - \sigma_s$ and $\bar{x} + \sigma_s$ is approximately 68%. The percentage of measurements between $\bar{x} - 2\sigma_s$ and $\bar{x} + 2\sigma_s$ is approximately 95%.

Note. The probability that the true mean is between $\bar{x} - \sigma_m$ and $\bar{x} + \sigma_m$ is approximately 68%. The probability that the true mean is between $\bar{x} - 2\sigma_m$ and $\bar{x} + 2\sigma_m$ is approximately 95%.

Example. Ali measured the length of the lab manual six times as follows: 30.3 cm, 30.7 cm, 30.5 cm, 30.1 cm, 29.8 cm and 30.6 cm. What is the best estimate of the length of the manual?

$\bar{L} = 30.333333\ cm$, $\sigma_s = 0.338624669\ cm$ and $\sigma_m = 0.138242942\ cm$
The best estimate of the length of the lab manual is given by: $\bar{L} \pm \Delta\bar{L} = 30.33 \pm 0.14\ cm$

Example. Suppose that five students measured the voltage drop (V) across a resistance (R). The measurements in volts were: 5.45 volt, 5.44 volt, 5.43 volt, 5.46 volt and 4.43 volt. What is the voltage drop on the resistor?
$\bar{V} = 5.442\ volt$, $\sigma_s = 0.013038405\ volt$ and $\sigma_m = 0.005830952\ volt$
The best estimate of the voltage drop on the resistor is given by: $\bar{V} \pm \Delta\bar{V} = 5.442 \pm 0.006\ volt$

2.1.2 Systematic errors

Such errors in experimental observations usually come from the measuring instruments. They may occur because there is something wrong with the instrument or its data handling system, or because the instrument is wrongly used by the experimenter.

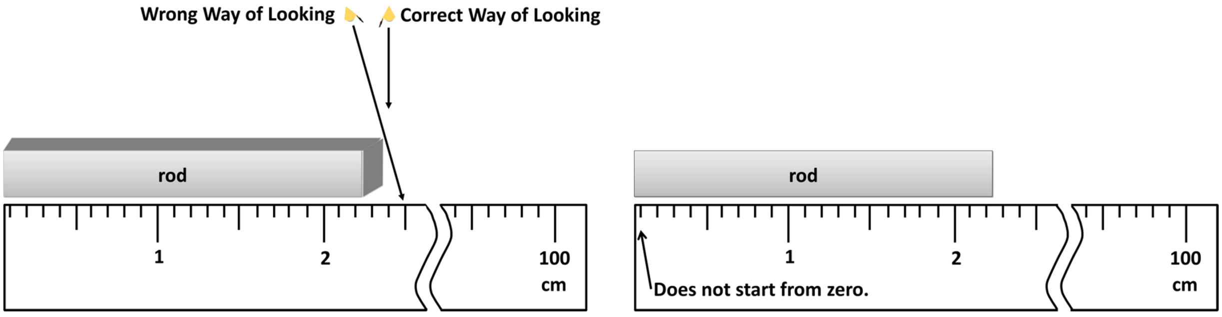

Figure 3: Examples of systematic errors.

2.2 Precision and Accuracy

Precision is the degree to which repeated measurements under unchanged conditions show the same results. In other words, precision is a measure of how consistent a measurement is. **Accuracy** is the degree to which a measurement agrees with the true value of the quantity being measured. In other words, accuracy is a measure of how close a measurement is to the true value.

Precision and accuracy are not related. A measurement can be precise without being accurate, and vice versa. For example, if you use a ruler to measure the length of an object and you get the same result every time, your measurement is precise. However, if the ruler is not calibrated properly, your measurement may not be accurate.

Precision and accuracy can be used for comparison only, and not as absolute concepts. For example, you can say that one measurement is more precise than another measurement, or that one measurement is more accurate than another measurement. However, you cannot say that a measurement is absolutely precise or absolutely accurate.

Note. Small random errors means **High Precision**.

Note. Negligible systematic errors means **High Accuracy**.

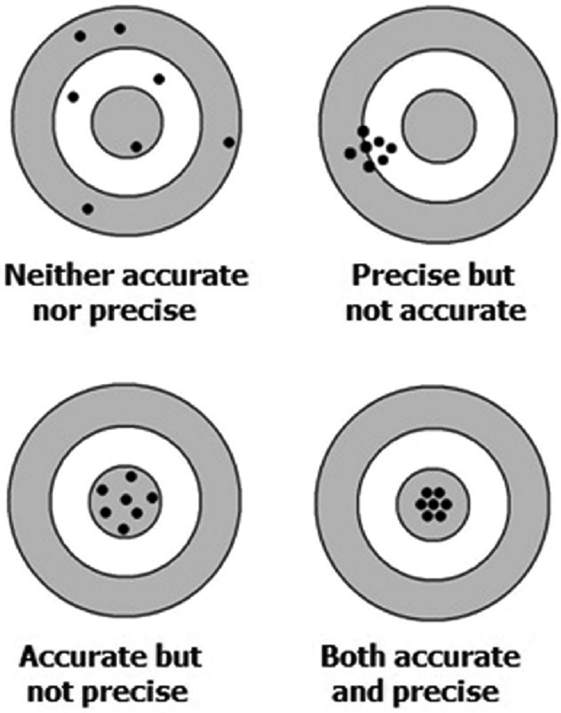

Figure 4: Analogy for precision and accuracy.

2.3 Comparison between measured values and accepted values

How do we decide if our result is accepted or not? We use the discrepancy test.

$$|x_{measured} - x_{accepted}| \leq 2\Delta x_{measured}$$

If the above inequality is true, the the result is accepted.

Example. Ali and Samia measured the speed of sound in air at standard temperature and pressure as follows: $v_A = 338 \pm 2\ m/s$ and $v_S = 325 \pm 5\ m/s$, respectively. If the known accepted value at standard temperature and pressure of the speed of sound is 331 m/s, which of the two results is accepted?

$D_A = |338 - 331| = 7\ m/s > 2 \times 2 = 4\ m/s \implies$ Ali's result is not accepted.
$D_S = |325 - 331| = 6\ m/s \leq 2 \times 5 = 10\ m/s \implies$ Samia's result is accepted.

Example. Layan conducted an experiment to determine the speed of light and obtained a value of $(3.09 \pm 0.03) \times 10^8$ m/s. The widely accepted value for the speed of light is 299792458 m/s. Is Layan's result consistent with the accepted value?

$D_L = \left|(3.09 \pm 0.03) \times 10^8 - 299792458\right| = 9 \times 10^6\ m/s > 2 \times 0.03 \times 10^8 = 6 \times 10^6\ m/s \implies$ Layan's result is not accepted.

Note. If the accepted value has uncertainty, then we look at the two intervals: $(x_{accepted} - \Delta x_{accepted}, x_{accepted} + \Delta x_{accepted})$ and $(x_{measured} - \Delta x_{measured}, x_{measured} + \Delta x_{measured})$. When the two intervals overlap, the result is accepted.

Example. Karim measured the mass of earth to be $(6.0 \pm 0.2) \times 10^{24}\ kg$. If the known accepted value of the mass of earth is $(5.974 \pm 0.004) \times 10^{24}\ kg$, is Karim's result accepted?

The interval of measured mass is $(5.8 \times 10^{24}, 6.2 \times 10^{24})\ kg$. The interval of reference mass is $(5.970 \times 10^{24}, 5.978 \times 10^{24})$ kg. Since the two intervals overlap, Karim's result is accepted.

2.4 Significant Figures

Significant figures are the digits in a number that contribute to the meaning of the number as a representation of a value of a physical quantity. They allow us to communicate the precision of our measurements and calculations. For example, if we measure the length of an object to be 10.0 centimeters, we are communicating that we are confident in the first two digits of the measurement, but not the last digit. They include all non-zero digits, in between zeros and leading zeros.

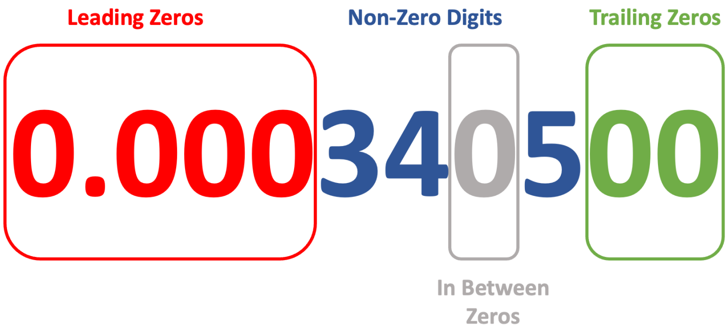

Figure 5: All digits are significant except leading zeros

Example. Here are some examples of significant figures:

22.44 cm has 4 significant figures.
11 km has 2 significant figures.
0.0010312 g has 5 significant figures.
100.0 sec has 3 significant figures.
0.0405017 Ω has 6 significant figures.
$3.024 \times 10^{10}\ kg$ has 4 significant figures.

2.4.1 Rounding

- If the first non-significant figure is larger than 5, then round the last significant figure up,e.g. 4.37 is rounded to 4.4 and 4.368 is rounded to 4.37.
- If the first non-significant figure is less than 5, then fix the last significant figure, e.g. 4.43 is rounded to 4.4 and 4.363 is rounded to 4.36.
- If the first non-significant figure equals 5, then round up if the last significant figure is odd and round down if it is even, e.g. 4.35 is rounded to 4.4 and 4.45 is rounded to 4.4.

2.4.2 Significant figures in calculated values

1) **Addition and Subtraction:** The number with the fewest decimal places limits the number of decimal places in the result.

Example. $R = 10.3\ cm + 108.76\ cm + 0.0349\ cm = 119.0949\ cm = \mathbf{119.1\ cm}$

Example. $R = 13\ kg - 3.1\ kg = 9.9\ kg = \mathbf{10\ kg} = \mathbf{1.0 \times 10^1\ kg}$

2) **Multiplication and Division:** The least number of significant figures in the numbers you are multiplying/dividing, determine the number of significant figures in the answer that answer should be rounded to it.

Example. The voltage (V) across unknown resistance and the current (I) through it were measured to be 1.7 volt and 11 mA, respectively. The resistance R can be estimated using Ohms law as follows:

$$R = V/I = 1.7/11 \times 10^{-3} = 154.545\Omega = \mathbf{150\Omega} = \mathbf{1.5 \times 10^2\Omega}$$

Example. If $x_1 = 1.8\ m$, $x_2 = 2.346\ m$ and $x_3 = 7.86\ m$, then $R_1 = x_1 x_2/x_3$ and $R_2 = x_3/x_2$ can be calculated as

$$R_1 = (1.8)(2.346)/7.86 = 0.537m = \mathbf{0.54m}$$

$$R_2 = 7.86/2.346 = 3.35038363171 = \mathbf{3.35}$$

3) **Functions:** The number of significant figures that should be kept in the result must equal the number of significant figures in the argument of the function.

Example.

$$\sin(12°) = 0.20791169081 = \mathbf{0.21}$$

$$\exp(2.10) = 8.16616991257 = \mathbf{8.17}$$

$$\cos(35.0°) = 0.81915204428 = \mathbf{0.819}$$

$$\sqrt{\frac{2.3 \times 4.57}{1.2}} = 2.95958893542 = \mathbf{3.0}$$

4) **Uncertainty:** Experimental uncertainty should be rounded to one significant figure unless the leading digit in the uncertainty is 1, then it is left with two significant figures.

Example. If the mean value of a set of measurements is $L = 6.3234\ cm$ and the standard deviation of the mean is $\Delta L = 0.0250\ cm$, the reported result should be as $L = 6.32 \pm 0.02\ cm$

Example. If the mean value of a set of measurements is $M = 3.5555\ kg$ and the standard deviation of the mean is $\Delta M = 0.01389\ kg$, the reported result should be as $L = 3.556 \pm 0.014\ cm$

2.5 Combination of Uncertainties

2.5.1 Constant Multiplier

Suppose that $R = cX$, where c is a constant, X is a measured quantity, then $\Delta R = c\Delta X$

Example. A physics student measured the length of one tile to be 30.0 ± 0.2 cm. If he wants to calculate the width of a room having 17 tiles across its width, then the student correctly calculated the width of the room as follows
$W = 17 \times 30.0 \text{ cm} = 510$ cm
$\Delta W = 17 \times 0.2 = 3.4$ cm
Therefore, $W \pm \Delta W = 510 \pm 3$ cm

2.5.2 Addition and Subtraction

If X and Y are two measured quantities with uncertainties ΔX and ΔY, then the uncertainty in $R_1 = X + Y$ and $R_2 = X - Y$ is $\Delta R_1 = \Delta X + \Delta Y$ and $\Delta R_2 = \Delta X + \Delta Y$.

Example. The mass of an empty bottle is $M_{empty} = 25.7 \pm 0.2$ g and the mass of the bottle full of liquid is $M_{full} = 72.3 \pm 0.3$ g . The mass of the liquid in the bottle is then
$M_{liquid} = M_{full} - M_{empty} = 72.3 - 25.7 = 46.6$ g
$\Delta M_{liquid} = 0.2 + 0.3 = 0.5$ g
Therefore, $M_{liquid} \pm \Delta M_{liquid} = 46.6 \pm 0.5$ g

2.5.3 Multiplication and Division

If $R = XY$ or $R = X/Y$, then we can find the uncertainty in R using

$\Delta R/R = \Delta X/X + \Delta Y/Y$

Example. The area of a rectangular plate was found by measuring its length and its width. The length was found to be 8.27 ± 0.05 m, while the width was found to be 5.12 ± 0.02 m. What is the area of the plate?
$A = LW = 8.27 \times 5.12 = 42.3424$ m^2
$\Delta A/A = 0.05/8.27 + 0.02/5.12 = 0.00995219921$
Therefore, $\Delta A = 0.00995219921 \times 42.3424 = 0.4214$ $m^2 \implies A \pm \Delta A = 42.3 \pm 0.4$ m^2

2.5.4 Raising to a Power

If $R = X^n$, then we can find the uncertainty in R using
$\Delta R/R = n\Delta X/X$

Example. A student measured the side length of a cube to be $5.3 \pm 0.4cm$. What is the volume of the cube?
$V = L^3 = 5.3^3 = 148.877$ cm^3
$\Delta V/V = 3\Delta L/L = 3 \times 0.4/5.3 = 0.22641509434$
Therefore, $\Delta V = 0.22641509434 \times 148.877 = 33.708$ $cm^3 \implies V \pm \Delta V = 150 \pm 30$ cm^3

2.5.5 Other Functions

If $R = f(X)$, then we can find the uncertainty in R using
$\Delta R = f'(X)\Delta X$

Example.
- $R = \exp(X), \Delta R = \exp(X)\Delta X$
- $R = \ln(X), \Delta R = \Delta X/X$
- $R = \sin(\theta), \Delta R = \cos(\theta)\Delta\theta$, θ should be in radians.

Example. $R = \sin\theta$ and $\theta = 80° \pm 2°$
R= $\sin(80°) = 0.984810775$
$\Delta R = cos(80°) \times (2)(\pi/180) = 0.0060614648$
Therefore, $R \pm \Delta R = 0.985 \pm 0.006$