Komar University of Science & Technology (KUST)

LABORATORY MANUAL

For

GENERAL PHYSICS I

2013 - 2014 – Ver.3

Table of Content

1. Course Description & Objectives

This is a one credit-hour class that meets once a week for two hours and fifty minutes. Each meeting of the class focuses on a particular experiment described in this lab manual. Each experiment is designed to incorporate a new lesson on measurement, data, error, or graphical analysis in addition to illustrating a physical principle of the companion courses. The ordering of the experiments broadly follows the progress in the General Physics Lecture course.

This lab manual provides descriptions of the experiments which you will be doing this semester. It also explains some of the concepts required to be understood in order to successfully complete this course. The experiments in this course use relatively simple equipment and deal with well-established physics.

By performing these experiments, you will learn how to:

- Apply scientific methods in the interpretation of observations in nature, and discover mathematical relations between these observations.
- Develop ideas about how the physical world behaves and to plan, carry out, and analyze experiments to test those ideas.
- Understand the experimental uncertainty in physical measurements and introduces ways to minimize the experimental errors.

In general, the objectives of this course are:

1- To demonstrate some physical principles,
2- To allow students to learn and appreciate the techniques of careful measurement.

3- To promote problem-solving skills and critical thinking through collaborative and individual reflection and analysis.
4- To improve scientific writing skills through weekly reports.

2. General Policies

2.1 Physics Lab Safety

Safety in the laboratory is very important. The experiments performed in the laboratory are designed to be as safe as possible, but caution is always advised concerning the Use of the equipment. You must conduct yourself in a safe manner at all times in the laboratory, exercise caution in everything that you do, and report injuries, no matter how minor, immediately to the instructor.

All Laboratory Students, Assistants, Faculty, and Staff must abide by the following safety rules when using the Physics Laboratory. This list may be modified as deemed appropriate for specific situations.

1. Handle all equipment with care; make sure that you understand the proper use and limitations of all equipment. When in doubt, ask the instructor.
2. Read the instructions on all warning signs and follow.
3. Wear safety goggles for laboratory activities such as projectile motion, centripetal force, and other labs that involve rapid motion or acceleration of any kind. The goggles are provided by the department and each person in the lab must wear them.
4. Long hair and loose items of jewelry or clothing MUST be secured during work with rotating machinery.
5. Do not lift heavy equipment without assistance.
6. Each student MUST know the use and location of all first aid and emergency equipment in the laboratories and storage areas.
7. Each student must be familiar with all elements of fire safety: alarm, evacuation and assembly, fire containment and suppression, rescue and facilities evaluation.
8. NEVER aim or fire a projectile motion device at a person.
9. When using the Air Tracks:
   - Do not let air track carts run away from the user.
   - Catch the cart before it crashes into the bumper or travels off from the table.

- Do not let the cart hit the motion sensor.

10. Keep hands clear of any fan blades, moving parts, or projectile launchers (other than to pull the trigger).
11. Laboratory walkways and exits must remain clear at all times.
12. Glassware breakage and malfunctioning instrument or equipment should be reported to the Laboratory Assistant.
13. All accidents and injuries MUST be reported to the Laboratory Assistant or Faculty teaching affected lab section. An Accident Report MUST be completed as soon as possible after the event by the Laboratory Specialist.
14. No tools, supplies, or other equipment may be tossed from one person to another; carefully hand the item to the recipient.
15. *Closed toe shoes* and *long pants* must be worn in the lab. Sandals and shorts are not allowed.
16. Eating, drinking, and smoking are ***strictly prohibited in the laboratory***.
17. No unauthorized experiments are to be performed. If you are curious about trying a procedure not covered in the experimental procedure, consult with your laboratory instructor.
18. Casual visitors to the laboratory are to be discouraged and MUST have permission from the Teaching Assistant, Faculty Instructor of the section in question, or Laboratory Specialist to enter. All visitors and invited guests MUST adhere to all laboratory safety rules. Adherence is the responsibility of the person visited.

This list is not complete, but you should get the idea that safety is a serious issue and you must conduct yourself accordingly. Your instructor will review safety features of the laboratory and other safety issues with the class during the first session.

2.2 Required Materials

You must bring a scientific calculator, a ruler, graph paper and a protractor to lab.

2.3 Preparation & Proper Lab implementation

You should come prepared to the laboratory session by reading the lab manual ahead of time. Note all questions and areas of confusion which can be brought up in group discussions in the lab. You should also review any appropriate sections of the textbook.

For each experiment, a ***pre-lab assignment*** is given which is based upon the lab description. It is intended that the process of answering few questions about theory and procedure will better prepare the student to conduct the experiment. The answer sheet of each experiment must be submitted prior to the lab date. Your preparation should also include coming to lab with all accessories (calculator, rules, notebook, protractor, writing utensil, etc.). If you are the group leader for that week, you should have a preliminary plan of the work and be ready to discuss the work with the instructor and group members.

During lab session, you should attempt to make all measurements with as much care as possible. In many cases the difference between excellent results and complete chaos is the care with which simple measurements are made. No amount of careful calculation after the lab work is finished can compensate for improperly taken data. If the data are incorrect, the goal of the lab exercise will most likely be lost. The student who strives successfully to develop careful experimental techniques will be rewarded both by success in the lab as well as by preparation for future advanced laboratory work.

2.4 Absences and Tardiness

If you arrive late for lab, your lab participation grade will be reduced. If you are more than 15 minutes late or miss lab, you will not be allowed to join your group or make-up the lab unless you have made previous arrangements with your instructor or you have a legitimate excuse as determined by the instructor. Without previous arrangements or a legitimate excuse, you will receive a zero for that week's lab. If you are late or miss any make-up session, you will not be allowed to make-up the lab and will receive a grade of zero for that lab.

2.5 Academic Honesty

You should work together with your lab partners in taking and analyzing data, and you will find that discussing the experiment with your partners helps you to understand the results. However, you should record your own data, and the lab reports that you turn in **must** be your own work in your own words. **You cannot copy or paraphrase your partner's reports.** Please refer to the section on Academic Conduct in the University's student handbook.

2.6 Grading Policy

Chemistry lab I is a separate class from CHEM1 class with one credit-hour. Your grade will be subdivided according to the following:

Lab Reports	20
Quiz	5
Total	**25**

3. Format of Lab Report

The grade on the lab reports will constitute the bulk of your lab grade. The format of the lab report is summarized below. Before you leave lab, you must record your data and obtain the instructor's signature on your data sheet. This sheet must be included in your report, so you should record your data neatly in lab. If you have time remaining in lab, you should work on your graphs and calculations.

You should not leave early unless you have finished your report. Lab reports are due one week after you perform the experiment at the beginning of the lab period. You will be deducted 20% per school day or part of a school day for late lab report.

Therefore, you should start working on your reports early in the week; this allows you time to seek help if you are having trouble.

Title Page

Lab reports have title page, it would be a single page that states:

- The title of the experiment.
- Your group no. (if any)
- Your name and the names of any lab partners.
- Your instructor's name.
- The date the experiment was performed.

Introduction/Purpose

Usually the Introduction is one paragraph that explains the objectives or purpose of the lab. In one sentence, state the hypothesis. Sometimes an introduction may contain background information. You need to state the purpose of the experiment, what is to be done, or why you did it.

Data

Original data obtained from your procedure is usually presented in tables with units. This section should also include:

- Estimated uncertainties of measurements (random error)
- Possible sources of error, particularly systematic error

Calculation, Results & Discussion

The Data section contains numbers. The results section contains any calculations you made based on those numbers. You need to include the formula used, then put sample numbers into the formula and show the calculation. Include units in sample; convert units as needed. Collect your results of calculations (possibly in a table). Then estimate the uncertainties in your results. Graphs should be included as needed.

You may wish to describe ways the work might have been improved. You also need to answer the ***Post-lab Questions*** in this section as well.

4. Uncertainty & Errors

No experiment is perfect. Certainly, you should perform your experiments carefully and use good equipment. When you make a measurement, however, you should consider the possible sources of error in that measurement.

In recording a measurement, the last digit is estimated; always estimate one digit past the digits that you can determine exactly. In other words, the last digit that you write down is the first uncertain digit.

For most instruments in this course, you must gauge the amount of uncertainty yourself. A good rule of thumb is that ***the uncertainty is one-half of the smallest division on the scale.*** If you are reading an electrical meter, you would record a larger uncertainty if the numbers are fluctuating than if the numbers are steady. In any case, your data must include the uncertainty of all measurements and justification for the numbers that you record for uncertainty.

4.1 Accuracy and Precision

Measurement of physical quantities is an essential part of the experimental physical science. It is assumed that there is a true value for each physical quantity, and the measurement is an attempt to find out that true value. Practically, there is always a difference between true value and measured value. The terms *accuracy* and *precision* describe two types of differences between measured value and true value of a quantity.

The ***accuracy*** of a measurement is how close the measured value is to the true value. For example, a value for the acceleration due to gravity will be determined. The accuracy of this value will be decided by how close it is to the true value of 9.8 m/s^2.

The ***precision*** of a measurement is referred to how much spread is the data. A more precise measurement is one that, when repeated, tends to yield nearly the same number. High precision does not necessarily imply high accuracy. See Table 1 below that illustrates the sets of measurements of acceleration due to gravity made by two students named Taban and Zardasht. You can see that Taban's readings are very close to each other and to the mean value, but not close to the true value of acceleration (9.8). While Zardasht readings are more deviated from the mean value but his mean is closer to the true value of acceleration. Therefore, we can say Taban's readings are more precise but Zardasht's measurements are more accurate.

Table 1

	Taban	Dev.	Zardasht	Dev.
Measurement 1	8.70	0.04	9.72	0.04

Measurement 2	8.75	0.01	9.86	0.10
Measurement 3	8.77	0.03	9.70	0.06
Mean	8.74		9.76	

In general, the best reliable measurements are those have both high accuracy and high precision.

4.2 Experimental Errors

Uncertainty in a measurement can arise from three possible origins: the measuring device, the procedure of how you measure, and the observed quantity itself. Usually the largest of these will determine the uncertainty in your data.

Experimental errors can be divided into two different types: systematic errors and random errors.

- **Systematic Errors:** They are errors tend to be in the same direction for repeated measurements, giving results that are either consistently above the true value or consistently below the true value. In many cases such errors are caused by some defect in the experimental apparatus such as improper calibration of measuring instrument. Frequent calibration to the instruments will help to reduce systematic errors.

  A second type of systematic error is failure to consider some parameters affecting your measurements. For example, friction in Newton's law experiment is neglected as it is difficult to measure but it will cause a systematic error. There are certain ways to reduce the impact of systematic errors depending on the type of experiment.

  In general, when your results are highly deviated from the true value, this is an indication of systematic error and you need to suggest a possible reasonable cause for such error.

- **Random Errors:** These errors are produced by unknown and unpredictable variations in the whole experimental process. Such errors are:

❖ fluctuations in temperature or line voltage

- mechanical vibrations of the experimental setup
- Inability of observer to estimate the last digit the same way every time in his/her measurement readings.

Random errors are difficult to eliminate but can be determined in a prescribed way. It has been proved empirically that random errors can be represented by normal distribution function, when a histogram of frequency distribution of the results give a bell-shaped curve with a peak at the mean. This function is also called the "Gauss distribution function".

4.3 Significant Digits

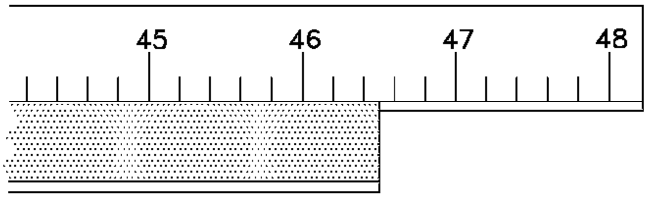
Most of physical experiments usually include more than one measurement and the measured data is used to calculate another quantity or parameter. The numbers expressing those parameters should have the right number of digits which we call the ***significant digits***. For example, if you put your weight as 153.2346657 lbs, that would not make much sense. If it were expressed as 153 lbs, that would make more sense, since the usual scale measures weight to the nearest pound. Similarly, when you present your results for a given experiment, the figures should contain no more digits than necessary. Some instruments have their significant digits mentioned; therefore your readings must be within these digits. The following rules should be followed to determine the number of significant digits of your final results:

1. In addition or subtraction, the number of decimal digits in the answer is determined by the number having the lowest number of decimal digits,
2. In multiplying or dividing, retain as many digits in your result as the number of digits in the least precise quantity used in your calculations,
3. Keep only a reasonable number of significant digits,
4. Round the values correctly.

4.4 Numerical Estimates of Uncertainties

For this laboratory, we will estimate errors with four methods, which are described below. You need to decide which technique you are using in a particular experiment.

4.4.1 Upper Bound



If only one measurement was taken, use ½ the smallest scale division of the measuring device. The figure below shows a meter stick graduated with centimeters used to measure the length of an object. We can say that our result is somewhere between 46.4 cm and 46.6 cm. We assume as an upper bound of our uncertainty, an amount equal to half this width (in this case 0.1 cm). The final result can be written as:

L = (46.5 ± 0.1) cm

4.4.2 Percentage Error and Percentage Difference

In some cases, you measure a parameter that has a true known value named as theoretical. You need to determine how close your experimental value is compared to the published result. This is usually performed by finding the percentage error of experimental value compared to the theoretical value. The percent difference is given by the equation:

$$\%\boldsymbol{Error} = \left|\frac{(\boldsymbol{experimental} - \boldsymbol{theoretical})}{\boldsymbol{theoretical}}\right| \boldsymbol{x}\ \mathbf{100}\% \quad \text{.................. } \textbf{Eq.1}$$

In other cases, you measure a quantity by two different methods then you will have two different experimental measurements, but the true value is not known. In this case you compare the two experimental values to determine the percentage difference between the two values. Assume your two values are E_1 and E_2, then the experimental difference will be as in the equation:

$$\%\boldsymbol{Difference} = \frac{|E_2 - E_1|}{|E_1 + E_2|/2} \times \mathbf{100}\% \quad \text{.....................................} \textbf{ Eq.2}$$

4.4.3 Estimation of mean Value (2/3 method)

For data in which there is random uncertainty, we usually compare each measurement x_i of number n measurements with the mean value x_i, to take only the close readings and exclude the ones spread far from the mean. Mean value is calculated by equation Eq.3. The interval around the mean that contains about 2/3 of the measured points is to be considered. Half size of this interval is a good estimate of the error in each measurement. A range that always includes all of the values is generally less meaningful.

$$\overline{x} = \frac{(\sum_{i=1}^{n} x_i)}{n} \quad \text{.. Eq.3}$$

4.4.4 Standard Deviation

When multiple measurements are taken for the same quantity (repeated measurement), you may use the standard statistical method to calculate the standard deviation function from square root of differences for each measured value from the mean. You can use the standard deviation function on your calculator, or, use the following function:

$$\sigma_{n-1} = \sqrt[2]{\frac{1}{n-1}\left(\sum_{i=1}^{n}(x_i - \overline{x})^2\right)} \qquad \overline{x} = \frac{(\sum_{i=1}^{n} x_i)}{n} \quad \text{.................. Eq.4}$$

Where, σ_{n-1} is the standard deviation from the mean, x_i is your measurement, $\bar{x}$ is the mean value, and n is the number of measurements. ***Probability theory states that approximately 68.3% of all repeated measurements should fall within a range of plus or minus σ_{n-1} from the mean. Furthermore, 95.5% of all repeated measurements should fall within the range of $2\sigma_{n-1}$ around the mean.***

4.4.5 Standard Error

The precision of the mean is an important issue, since it is the best estimate of the true value. The precision of the mean is indicated by a quantity called "standard error", whose symbol is a and calculated by :

$$\boldsymbol{\alpha = \frac{\sigma_{n-1}}{\sqrt{n}}} \text{..} \textbf{Eq.5}$$

Ex: You have measured the time of experiment for five times and recorded the readings 5.6, 6.1, 6.5, 7.2, 7.9 s. You need to calculate the mean value and the standard error as follows:

$$\bar{x} = \frac{(5.6 + 6.1 + 6.5 + 7.2 + 7.9)}{5} = 6.66 \cong 6.7$$

From equation Eq.4 we calculate the standard deviation:

$$\sigma_{n-1} = \sqrt{\frac{1}{5-1}\{(5.6-6.7)^2 + (6.1-6.7)^2 + (6.5-6.7)^2 + (7.2-6.7)^2 + (7.9-6.7)^2\}}$$

$$\sigma_{n-1} = 0.8$$

$$\alpha = \frac{0.82}{\sqrt{5}} = 0.366 \cong 0.4$$

The significance of a is that if several groups of n measurements are made, each producing the value for the mean. 68.3% of the means should fall in the range 6.7 ±0.4. In other words, there is a 68.3% probability that the true value lies in this range.

4.5 Propagation of Uncertainty

In many experiments, the measured values are used to determine other quantities via certain formula. When we measure quantities used in a formula and each has an associated uncertainty, we need to determine the uncertainty of the calculated quantity as well. We deal here with how to propagate uncertainties of measured values to obtain the uncertainty of a computed quantity.

4.5.1 Combining Errors (Probability Theory)

Suppose variables $x, y, and\ z$ are measured, and their means $\bar{x},\ \bar{y}, and\ \bar{z}$ and standard errors $\alpha_{x},\ \alpha_{y}\ ,\ and\ \alpha_{z}$ are determined. Some quantity A($\bar{x}, \bar{y}, \bar{z}$) is calculated from the mean values $\bar{x}, \bar{y}, and\ \bar{z}$. Normally, a will have a standard error as well, therefore we need to calculate it in terms of $\alpha_{x},\ \alpha_{y}\ ,\ and\ \alpha_{z}$. Probability theory states that the appropriate relationship is:

$$(\alpha_A)^2 = (\partial A/\partial x)^2(\alpha_x)^2 + (\partial A/\partial y)^2(\alpha_y)^2 + (\partial A/\partial z)^2(\alpha_z)^2 \qquad \textbf{Eq.6}$$

From your study of calculus, you can derive an equation for α_A **for** any function needed using equation Eq.6. Here below few examples of standard error equations for addition, multiplying and dividing functions:

For $A = x + y$ $\qquad (\alpha_A)^2 = (\alpha_x)^2 + (\alpha_y)^2$ **Eq.7**

For $A = x.y$ $\qquad (\alpha_A)^2 = y^2(\alpha_x)^2 + x^2(\alpha_y)^2$ **Eq.8**

For $A = \frac{x}{y}$ $\qquad (\alpha_A)^2 = \left(\frac{1}{y^4}\right)\left[y^2(\alpha_x)^2 + x^2(\alpha_y)^2\right]$ **Eq.9**

4.5.2 Random Functions (Minimum and Maximum)

Based upon the error of the quantity that you determined, you can find the maximum and minimum values of the quantity that you are calculating. The value that you found should be roughly midway between these two quantities. Then if you split the difference between the maximum and minimum you should obtain a reasonable estimate of the error.

Example: Suppose you measure an angle to be (47.3± 0.5), and you want to determine the error of sin(47.3 ± 0.5). You will find that sin(47.3) = 0.735. That means, your calculated results can be as large as 47.8, and as small as 46.8, and therefore you should calculate sin(47.8) and sin(46.8). So your calculated value is 0.735 but it can be as low as 0.729 and as high as 0.741 and therefore, if you halve the difference between 0.729 and 0.741 you get a reasonable error estimate of 0.006. So you should report your value as 0.735±0.006.

5. Graphing Techniques

In physics, data tables are not enough expression of the relations between measured parameters. Physicists look for mathematical relations between measured parameters. Plotting measured data on a graph paper or on computer will help to illustrate that relationship and find the mathematical expression for it. Most of graphs in this lab experiments will use rectangular Cartesian coordinates. The horizontal axis is called abscissa (x axis) and the vertical is the ordinate (y axis). You need to follow the rules below in plotting your graph:

1- Put an informative title for each axis with units of measurement.
2- The graph must have a title as well.
3- Select a scale for each axis that your data will fill all the graph paper or graph area. It is not necessary that both axis have the same scale.
4- Scale should start from zero (0) point as all physical data are positive.
5- The more points measured the better fit line we get. It is preferred to have at least 5 point to plot a graph.
6- All graphs should be plotted as points not smooth lines unless the mathematical trend of the data is known as linear or exponential. If the data is linear, there is a "best fit" straight line that most nearly goes through all of the data points.

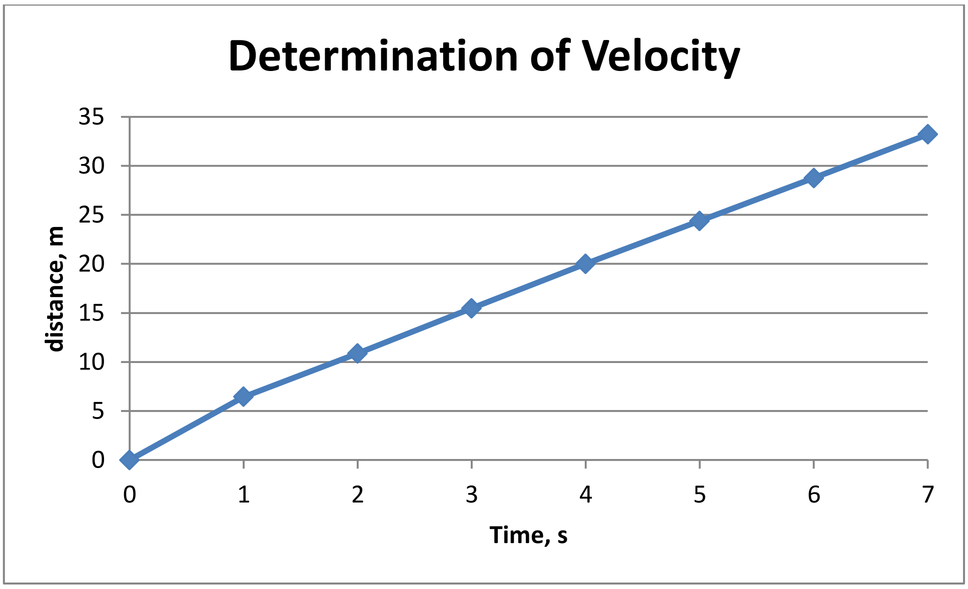
Generally, the variable that you set or control appears on the horizontal axis, while the variable that you measure appears on the vertical axis.

Ex: The data in Table 2 presents distance versus time to calculate velocity according to the equation:

$$v = \frac{\Delta z}{\Delta t}$$

Table 2

Z (m)	T (s)	V m/s
0	0	
6.45	1	6.45
10.86	2	4.41
15.47	3	4.61
20.01	4	4.54
24.38	5	4.37
28.75	6	4.37



From the graph above, it can be seen that the distance is proportional to the time (straight line) with almost constant velocity, except in the starting point when there was accelaration to reach the steady state velocity.

Experiment 1: Measurements and Uncertainty

Objectives

1- To demonstrate the concept of uncertainty in simple measurement by using meter-stick, Vernier caliper and a micrometer, and use this measurement to calculate the density of certain objects.
2- To learn accuracy and precision measurement skills by repeated measurement of the quantities.
3- To apply the statistical concepts of mean, standard deviation from mean, and standard error to the measured data.
4- Demonstrate the propagation of uncertainty by calculating the errors of measurement.

Theory

In section 4, the "Uncertainty & Errors" of this manual (page 8), the uncertainty and types of experimental errors are discussed. You need to read thoroughly. In this lab experiment we will try to determine those errors in the measurement of length of a lab table and density of solid objects.

The possible systematic error in the meter stick is its uneven edges and shrink or expansion with time. Similarly, the Vernier caliber and micrometer may have manufacturing defects or incorrect calibration. While random errors can be associated to difficulty in interpolating between the smallest marked scale divisions in the same amount every time. The best way to reduce the random errors effect is take several measurements and average them.

Note: We usually specify any measurement by including an estimate of the random uncertainty. Since the random uncertainty is unbiased we note it with a ± sign. So if we measure a time of 7.6 seconds, but we expect a spread of about 0.2 seconds, we write as a result:

$$t = (7.6 \pm 0.2)\ s \quad \text{--} \quad \textbf{Eq. 1.1}$$

Indicating that the uncertainty of this measurement is 0.2 s

Uncertainty of Calculated Area

For this experiment, consider the area A of the table as calculated from the mean of measured values of the length $\bar{L}$ and mean width $\bar{W}$, by the following:

$$\boldsymbol{A = \bar{L}\,x\,\overline{W}}$$ --

Eq. 1.2

If we apply equation Eq.8 on the area, we can calculate the standard error $\boldsymbol{\alpha_A}$ as follows:

$$\boldsymbol{\alpha_A = \sqrt{\bar{L}^2\alpha_W^2 + \bar{w}^2\alpha_L^2}}$$ ---

Eq. 1.3

This equation gives the standard error of the table area, $\boldsymbol{\alpha_A}$**,** in terms of length and width of the table and their associated standard errors. Note that a similar equation applies for standard deviation from the mean:

$$\boldsymbol{\sigma_{n-1}^A = \sqrt{\bar{L}^2(\sigma_{n-1}^W)^2 + \overline{W}^2(\sigma_{n-1}^L)^2}}$$ ----------------------------

Eq. 1.4

Measurement of Density

Density is defined as the mass of a substance divided by its volume.

$$\boldsymbol{\rho = \frac{M}{V}}$$ ---

Eq. 1.5

For a cylinder the volume is given by :

$$\boldsymbol{V = \frac{\pi r^2 l}{4}}$$ --

Eq. 1.6

where:

V = volume

r = radius

d = diameter

l = length

π = pi, the ratio of the circumference of a circle to its diameter (=22/7).

Substitute the expression for volume into the expression for density to obtain a formula
in terms of the measurable quantities.

$$\rho = \frac{4M}{\pi d^2 L}$$ --

Eq. 1.7

The quantities M, d, and L will be determined by measuring each of them four times independently and calculating the mean and standard error for each quantity. The standard error of ρ is related to the standard error of M, d, and L by

$$(\alpha_\rho)^2 = \left(\frac{\partial\rho}{\partial M}\right)^2(\alpha_M)^2 + \left(\frac{\partial\rho}{\partial L}\right)^2(\alpha_{LM})^2 + \left(\frac{\partial\rho}{\partial d}\right)^2(\alpha_d)^2$$ --------------

Eq. 1.8

Pre-lab questions

1- State the number of significant digits in each of the following numbers:

 a- 35.20
 b- 0.0560
 c- 9000
 d- 1.6800

2- Using the rules of significant digits, perform the following calculations.

 (a) 23.60 X 1.34 (b) 3.4 $\sqrt{6.315}$ (c) 1.234 + 2.7 + 12.89

3- What class of errors is assumed to be the basis for statistical variations in measurements?

(a) Personal (b) systematic (c) random

Materials & Equipment

Meter stick

Lab table

Lab balance

Vernier Caliper

Micrometer

cylinders of four different types of metal

Procedure

Measurement of length

1- Place the 2-meter stick along the length of the table near the middle of the width and parallel to one edge of the length.

2- Let x stand for the coordinate position in the length direction. Read the scale on the meter stick that is aligned with one end of the table and record that measurement in the data table as x_1 meters. Read the scale that is aligned at the other end of the table and record that measurement in the Data Table as x_2 meters. Note that the smallest-marked scale division of the stick is 1 mm. therefore; each coordinate should be estimated to the nearest 0.1 mm (nearest 0.0001 m).

3- Repeat steps 1 and 2 nine times to have total of 10 measurements of the table length. To the possible extend, place the stick on the same line of the table each time in order to avoid the systematic error of uneven width of the table along its length.

4- Repeat steps 1-3 for 10 measurements of the width of the table, and record your date in table 1

Length (cm) (L)	Width (cm) (W)

Table 1

Calculations

1- After all measurements are completed, perform the subtractions of $x_2 - x_1$ to get 10 values of L_i and W_i in the calculations table.

2- Using equation Eq.3, Eq.4, and Eq.5 to calculate the mean length $\bar{L}$ and mean width $\bar{W}$, standard deviation from the mean $\sigma_{n-1}^{L}$and $\sigma_{n-1}^{W}$and the standard error $\alpha_L$and α_W in two significant figures. Initially record the results of $\bar{L}$ and $\bar{W}$ with full decimal points in a separate sheet. Then make the values of $\sigma_{n-1}^{L}$and σ_{n-1}^{W}in one significant digit. Next record the value of $\bar{L}$ and $\bar{W}$ so that they have their most significant digit in the same decimal place as the standard error $\alpha_L$and α_W. Record these data in your Calculations Table.

3- Using the original values of $\bar{L}$ and $\bar{W}$, $\sigma_{n-1}^{L}$and $\sigma_{n-1}^{W}$and the standard error $\alpha_L$and α_W to calculate the standard deviation $\sigma_{n-1}^{A}$and standard error of the areaα_A. Record them in the calculation table to ***one*** significant figure.

4- Using the values of $\bar{L}$ and $\bar{W}$in equation Eq.1.2, calculate the area of the table, determining the number of significant figures in the area by a procedure similar to the one used above to determine the significant $\bar{L}$ and $\bar{W}$. Let the most significant digit in the calculated area be in the same decimal place as the most significant digit in α_A.

Measurement of Density

1- Measure the dimensions of the four cylinders. Use the Vernier calipers to take at least three measurements of each dimension (that is, each member of your group should measure each dimension).

2- Use the balance to find the mass of the cylinder. What units did you measure the Objects in?

3- Calculate the mean of each dimension for your length and diameter values and list them in the calculations table.

5- Use equation Eq.1.7 to calculate the density of each cylinder from the mean values for the mass, length and diameter. Remember to convert the units of measurement to SI units for calculation.

6- Record your data in table 2

Cubic	L_1/ cm			L_2 /cm			L_3/cm			$\overline{L_1}$	$\overline{L_2}$	$\overline{L_3}$	$\overline{V}$ (cm^3)= $\overline{L_1}$ * $\overline{L_2}$ * $\overline{L_3}$	M (g)	$\rho = \frac{m}{\overline{V}}$
	L	L	L	L	L	L	L	L	L						
1															
2															
3															
4															

Calculations

5- Calculate the standard error of density $\boldsymbol{\alpha_\rho}$ from equation Eq. 1.8. Let the most significant digit in the calculated density be in the same decimal place as the most significant digit in α_ρ.

6- For the purpose of this experiment, assume that the density of aluminum is 2.70 g/cm^3, the density of brass is 8.40 g/cm^3 , and the density of iron is 7.85 g/cm^3. Calculate the percentage error in your results for the density of each metal.

Post-lab Questions:

1- What percentage of your values of L_i fall in the range $\bar{L} \pm \sigma_{n-1}^{L}$?--------%

2- What percentage of your values of W_i fall in the range $\bar{W}\pm\sigma_{n-1}^{W}$? -------%

3- According to the theory of random errors, what percentage would be expected for the answers to question 1?

4- Based on your answers to Q1-3, are your data reasonably consistent with the assumption that only random errors are present in the experiment? State clearly the basis for your answer.

Experiment 2: Vectors and Net Force

Objectives

To verify that the sum of forces on an object at rest in equilibrium is zero.

Theory

Newton's second law of motion states that the acceleration produced by a net force on an object is directly proportional to the net force, is in the same direction as the net force, and is inversely proportional to the mass of the object:

$$\boldsymbol{a} = \frac{\boldsymbol{\Sigma F}}{\boldsymbol{m}} \quad \text{or} \quad \boldsymbol{\Sigma F} = \boldsymbol{m.a}$$ ----------------------------- **Eq. 2.1**

where the bold faced letters represent vector quantities. For the case when an object is not undergoing an acceleration (the velocity of the object is either 0, or the object is moving at a constant velocity), then $\Sigma F = 0$, which is the first condition for equilibrium. The sum of the forces ΣF is the algebraic sum of all the individual forces:

$$\boldsymbol{\Sigma F} = \boldsymbol{F1} + \boldsymbol{F2} + \boldsymbol{F3} + \ldots = \boldsymbol{0}$$ --------------------------------- **Eq. 2.2**

Take for example the case of a box that is hanging motionless from a rope. The force that is due to the weight of the object, $F1$ must be equal and opposite to the direction of another force, $F2$, if the box is not accelerating. $F2$ must be the "support force", in this case, the tension in the rope that acts in the upward direction to balance the force downward. Weight is a force, and by Equation 2.1, the force $F1$ on the box downward is:

$$\boldsymbol{W} = \boldsymbol{m \cdot g}$$ --- **Eq. 2.3**

where W is the weight and g is the acceleration due to gravity, $-9.8\, m/s^2$, where the negative sign indicates that gravity is acting in a downward direction. By the condition for equilibrium, $F1 + F2 = 0$, or $W + F2 = 0$, or $F2 = -W$.

Equation 2.2 deals with vector quantities; breaking this down into components yields three
equivalent scalar equations, each representing one of the spatial directions, x, y, or z:

$$\boldsymbol{\Sigma Fx = F_{1x} + F_{2x} + F_{3x} + \dots = 0}$$ ---------------------------- **Eq. 2.4**

$$\boldsymbol{\Sigma Fy = F_{1y} + F_{2y} + F_{3y} + \dots = 0}$$ ------------------------------- **Eq. 2.5**

$$\boldsymbol{\Sigma Fz = F_{1z} + F_{2z} + F_{3z} + \dots = 0}$$ ------------------------------- **Eq. 2.6**

Therefore, if the magnitude and direction of a force are known, then its components in each of these directions may be found using trigonometry. The x and y components can be found by the following equations assuming that the angle θ is defined as counterclockwise from the positive x axis:

$$\boldsymbol{F_x = F\, cos\, \theta}$$ -- **Eq. 2.7**

and

$$\boldsymbol{F_y = F\, cos\, \theta}$$ --- **Eq. 2.8**

The x and y components of a vector can be summed by means of the Pythagorean Theorem to produce the magnitude of the resultant vector; the angle indicating the direction of the resultant can be found by taking the inverse tangent of the ratio of the magnitude of the y and x components:

$$\boldsymbol{F = \sqrt{{F_x}^2 + {F_y}^2}_x}$$ -- **Eq. 2.9**

and

$$\boldsymbol{\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right)}$$ --- **Eq. 2.10**

For equilibrium of an object that is at the origin and being pulled by the force such as shown in the example above, another vector force whose x and y components are $+F_x$ and $+F_y$, respectively, must be applied. Furthermore, if the system is in equilibrium, the force vectors will form a closed figure when they are connected, head to tail, as shown in the Figure 2.1.

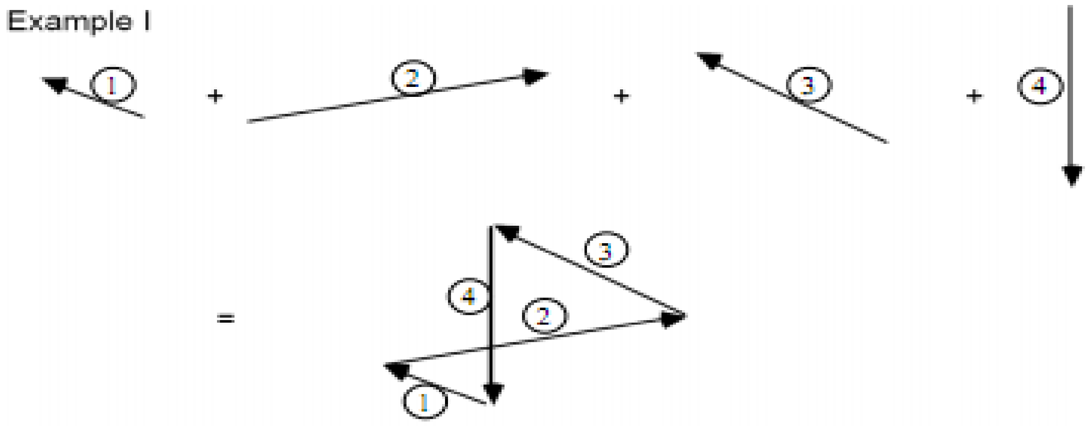


Figure 2.1 Closed system in equilibrium.

Pre-lab questions

1. Describe a typical scale that you might use for drawing force vectors on a piece of paper, e.g., how long might you choose to make a 1-N force? Assume that your forces are from 5 to 10 newtons, and pick a scale that results in a drawing that is as big as it can be (for maximum precision) while still fitting on a piece of paper.

2. Graphically calculate the vector sums of the two pairs of vectors shown below. As a check on your results, you should find that the magnitudes of the two sums are equal.

Materials & Equipment

- Force Table Apparatus
- Three Mass Hangers
- Small Laboratory Weights
- Sprit level
- Ruler
- Protractor

- Unknown mass
- Graph Paper

Procedure and Calculations

There are two parts in performing this experiment. The first is to calculate the third force (its magnitude and direction) that is required for a system of three forces in equilibrium. In the second part of the experiment, we will verify that the system of all three forces is in fact in equilibrium by the use of the force table.

PART I. Calculation of a third force that produces an equilibrium condition:

1. Record the given values for the masses of objects 1 and 2, m_1 and m_2, (in kilograms) and the associated angles, θ_1 and θ_2, with respect to the origin.
2. Calculate the magnitude of the forces, F_1 and F_2, that are associated with the weight of masses 1 and 2 respectively, by using equation 3. If the units of mass are kilograms and the units of g are m/s^2, then the units for the weights should be in Newtons.
3. Calculate the x and y components of F_1 and F_2 using equations 7 and 8.
4. Use equations 4 and 5 to find the components of the third force, F_{3x} and FF_{3y}
5. Use equations 9 and 10 to find the magnitude and direction (θ_3) of F_3.
6. Calculate the mass, m_3 , needed to produce the force, F_3, using equation 3. This is the mass that must be hung at an angle θ_3 so that an object subjected to the three forces is at equilibrium.

PART II. Verification that the system of all three forces is in equilibrium.

1. Adjust the force table to so that it is level horizontally. Make sure that the axis of rotation for every pulley is perpendicular to the radius of the force table.
2. Use the centering pin to anchor the ring to the center of the table.
3. Place pulleys at the given angles θ_1 and θ_2. Hang the two given masses, m_1 and m_2 , at their respective angles.
4. Add m_3 to the system at the calculated angle θ_3.
5. Verify that the ring is now in equilibrium by removing the centering pin. At the equilibrium position, the center of the table must coincide with the center of the ring after the centering pin is removed. NOTE: If the system is not in equilibrium (i.e., the ring is moving or not in the center of the table), keep the angle at θ_3 and adjust m_3 until equilibrium is reached.

6. Draw the force vectors, F_1, F_2, and F_3, for the condition of equilibrium found in step 5 by inserting a piece of paper under the system and tracing the direction of the three cords which connect the ring to m_1, m_2, and m_3.
7. Draw a vector diagram of the forces to scale:
   a. Each force can be represented by a straight line of the proportional length to the magnitude of that force and the same direction as that force. In order to draw the force vectors to scale and the appropriate length, use a scaling factor so that $1\ cm = 0.49N$. (Example) if $F_1 = 29.4N$, then the length of the vector should be: $29.4N \cdot \frac{1\ cm}{0.49N.} = 60cm$
   b. Record the values for the length of your scaled vectors, denoted respectively for F_1, F_2, and F_3 as a, b, and c on your data sheet.
   c. Draw the scaled vectors together with the appropriate angles, θ, so that they are added head to tail (the arrow end of one vector touches the straight end of the next vector, such as shown in Figure 1).
   d. The vector diagram will form a triangle when the three forces are in equilibrium.
8. If there are experimental measurement and random errors, the vector diagram will have a gap between the starting point of the first vector and the tip of the last vector (the final point). Draw a straight line from the starting point to the final point. This is the fourth vector which represents the error vector. See Figure 2.2 (below).
9. Use the same scale as above to find the length of the error vector in Newtons, and calculate the mass in kilograms to which this force would correspond. Record this as Δm_3 on your data sheet.

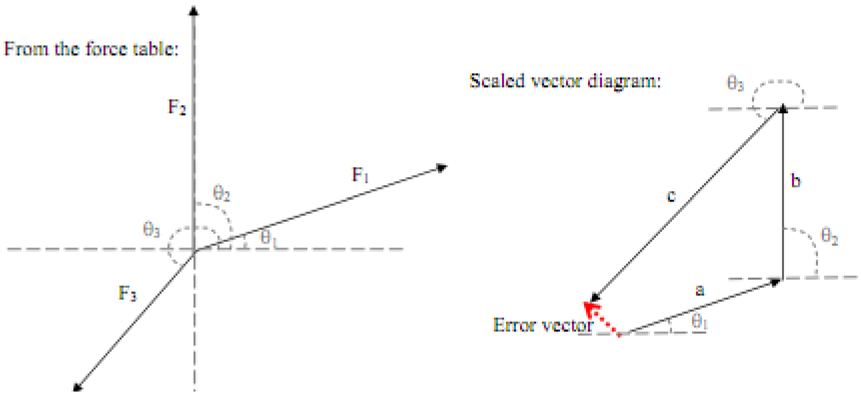


Figure 2.2 Error Vector.

Post-lab Questions:

1. For our system of three forces in equilibrium, the ring on the force table was in equilibrium. In addition, each mass was in equilibrium. What were the forces that acted on m_1?
2. If our system had been composed of two masses instead of three, is there any angle other than $\theta = 180^0$ for m_2 with respect to m_1 possible so that the system could be in equilibrium? Explain why or why not based on trigonometry.
3. For calculations with an ideal system, we usually assume that pulley and rope systems are massless and frictionless. In the specific system for three masses with the experiment that we performed, is it possible that the mass of the cords and friction against the pulleys played any role in our determined value for m3 and the error associated with it? Why or why not?

Experiment 3: Acceleration Due to Gravity: Inclined plane

Objectives

1. To measure linear acceleration due to gravity using distance and time.
2. To determine the relation between acceleration and **angle of inclination**

Theory

In physics, acceleration has a specific meaning. Acceleration is the rate at which speed changes. A cart accelerates as it rolls down a track. You can tell because the speed changes. From Experiment 2 you understood the meaning of vectors, therefore it is worthy to understand that acceleration has a vector nature. Vectors rule the universe. Gravitational acceleration, electric fields, nuclear forces, magnetic fields, all the things that tie our universe together are vectors.

In this experiment, you will measure the velocity of a cart at various points as it glides down a slightly inclined and nearly frictionless track. In addition you will learn several techniques for finding acceleration. When an object slides down an incline, there are three forces acting upon it: the normal force, (*N*) of the incline pushing up on the object, the weight of the object (*W*), and any frictional forces (F_{fr}). Figure 3.1 illustrates these forces. The dashed lines indicate the components of the object's weight along and perpendicular to the incline.
Any net force in the x-direction will cause the object to slide along the incline. Summing the x-components of the forces shown in Figure 3.1, we find that:

$$W_x - F_{fr} = ma_x \quad \text{Eq. 3.1}$$

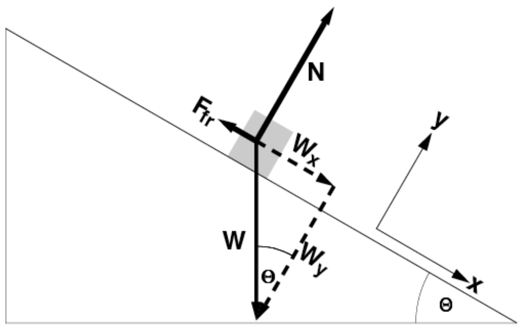


Fig. 3.1 Free-body diagram of an object sliding down an inclined plane

When the frictional force is very small, as will be the case in this experiment, it can be neglected,
so that

$$W_x = ma_x \text{--} \quad \textbf{Eq. 3.2}$$

The x-component of the object's acceleration is then

$$a_x = \frac{W_x}{m} = \frac{(mg\,sin\theta)}{m} = g\,sin\theta \text{ --------------------------------} \quad \textbf{Eq. 3.3}$$

For a fixed inclination angle, θ, measurement of the acceleration down the incline permits *g* to be determined experimentally. Note that because the acceleration is constant we can appeal to the familiar kinematics equations to describe the motion of the object as it moves down the incline.

$$\bar{r} = \bar{r}_0 + \bar{v}_0 t + \frac{1}{2}\bar{a}t^2 \quad \text{--} \quad \textbf{Eq. 3.4}$$

$$\bar{v} = \bar{v}_0 + \bar{a}t \quad \text{--} \quad \textbf{Eq. 3.5}$$

when the +x-direction is defined to be down the incline.

Experimentally, we will determine the *velocity* of the object after it has traveled specific distances along the incline. We can describe this mathematically by combining the previous two equations and eliminating the time variable,

$$x - x_0 = \frac{1}{2a_x}(v_x)^2 \quad \text{---} \quad \textbf{Eq. 3.6}$$

The left side of the equation ($x - x_0$) represents the distance traveled by the object. The acceleration of the object along the incline can be *determined from the slope of a linear plot involving the distance the object travels and its velocity.*

If the angle of an incline with the horizontal is small, a cart rolling down the incline moves slowly and can be easily timed. Using time and position data, it is possible to calculate the acceleration of the cart. When the angle of the incline is increased, the acceleration also increases. The acceleration is directly proportional to the sine of the incline angle, (θ). A graph of acceleration versus sin(θ) can be extrapolated to a point where the value of sin(θ) is 1. When sin(θ) is 1, the angle of the incline is 90°. This is equivalent to free fall.

Pre-lab Questions

1. Should x be measured horizontally, or along the slope of the track?
1. It is not possible to measure θ accurately with a protractor. How can θ be determined based on the distance between the feet of the air track and the height of the wood block?
2. One of the timing devices Galileo used was his pulse. Drop a rubber cart from a height of about 2 m and try to determine how many pulse beats elapsed before it hits the ground.
3. What was the timing problem that Galileo encountered?
4. Now measure the time it takes for the rubber cart to fall 2 m, using a wrist watch or wall clock. Did the results improve substantially?

Materials & Equipment

1. Air track with two photogates
2. Cart, approximately 8 cm long
3. Rubber Cart,
4. Timer or stop watch
5. Ruler and Meter Stick

Procedure

Measuring Acceleration

1. Set the inclined plain at an angle. Do not change the angle for the first part of the experiment.
2. Put the cart on the inclined plain at different distance and leave the cart to start rolling
3. Record the time for each distance (from starting point until end point.

4. Record your date in table 3.1 and calculate the slope.
5. Use equation 3.4 to calculate acceleration.
6. Chang the angle of the inclined plain at different angle and repeat step 2-5 to calculate acceleration.

r (m)	$t_1\ (sec)$	$t_2\ (sec)$	$t_3\ (sec)$	$t\ (sec) = \frac{(t_1 + t_2 + t_3)}{3}$	$t^2 (sec^2)$
0.1 (10 cm)					
0.2					
0.3					
0.4					
0.5					

Table 3.1

Graphing & Analysis

1. Use the data from table 3.1to plot the graph between distance and time for different angle and calculate slope. After finding slope calculate acceleration and gravitational acceleration (g).
2. Plot the graph between acceleration which are founded and angles of inclined plain
3. Discuss your graphs and the source of errors in the experiments.

Experiment 4: Coefficient of Friction: Influencing Factors

Objectives

1. Determination of the frictional force acting on a moving system
2. Determination of static Coefficient of Friction and the Kinetic Coefficient of Friction on a horizontal board.
3. Demonstration that the Static Coefficient of Friction is greater than the Kinetic Coefficient of Friction.
4. Determination of the influencing factors on coefficient of Friction.

Theory

Friction is the force resisting the relative motion of solid surfaces, fluid layers, and material elements sliding against each other. The direction of frictional force on each of the two surfaces is opposite to its motion. Dry Friction is the resistance to lateral motion of two solid surfaces in contact. The two types of dry friction are *Static Friction* between non-moving surfaces and *Kinetic Friction* (sometimes called sliding friction or dynamic friction) between moving surfaces. It was found experimentally that frictional forces depend on the nature of the materials in contact, their roughness, and the normal force between the two surfaces. The normal force is defined as the net force compressing two parallel surfaces together; and its direction is perpendicular to the surfaces. When a solid object is moving on a horizontal surface, the only component of the normal force is the force due to gravity, where:

$F_n = m\,.g$

The friction force is directly proportional to the normal force:

$\boldsymbol{F_f \leq \mu\, F_n}$ .... **Eq. 4.1**

Where F_f is the force of friction exerted by each surface on the other, it is parallel to the surface, in a direction opposite to the net applied force.

μ is the coefficient of friction, which is an empirical property of the contacting materials,

F; is the normal force exerted by each surface on the other, directed perpendicular (normal) to the surface.

The coefficient of friction (CO F) is a dimensionless scalar value which describes the ratio of the force of friction between two bodies and the force pressing them together, therefore, it is not a function of mass or volume; it depends only on the material. For instance, a large aluminum block has the same coefficient of friction as a small aluminum block. However, the magnitude of the friction force itself, depends on the normal force, and hence on the mass of the block. From eq. 4.1 it can be seen that the frictional force is independent on the apparent area of contact of the two surfaces.

Dry friction can be found in two kinds:

1. *Static Friction*: is friction between two or more solid objects that are not moving relative to each other. For example, static friction can prevent an object from sliding down a sloped surface. The coefficient of static friction, is typically denoted as us. The static friction force must be overcome by an applied force before an object can move. The maximum possible friction force between two surfaces before sliding begins is the product of the efficient of static friction and the normal force:

$$\boldsymbol{F_S \leq \mu_S F_n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{Eq. 4.2}$$

2. *Kinetic Friction*: (or Dynamic) friction occurs when two objects are moving relative to each other and rub together (like a sled on the ground). The coefficient of kinetic friction is typically denoted as μ_k. the frictional force F_k for kinetic friction is given by

$$\boldsymbol{F_k \leq \mu_k F_n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{Eq. 4.3}$$

The kinetic frictional force is constant while the object is in motion. Thus, it is independent on the speed of motion.

Both static and kinetic coefficients of friction depend on the pair of surfaces in contact; for a given pair of surfaces, the coefficient of static friction is usually larger than that of kinetic friction

The influencing factors on the COF for any two materials depends on system variables like temperature, velocity, atmosphere and also what are now popularly described as aging and de-aging times; as well as on geometric properties of the interface between the materials

Note that both Eq. 4.2 and Eq.4.3 refer to the case of horizontal surface when frictional forces are perpendicular to the normal forces. When enough force is exerted to overcome static frictional force, that same force is sufficient to accelerate the object motion as the kinetic frictional force will be less than the applied force

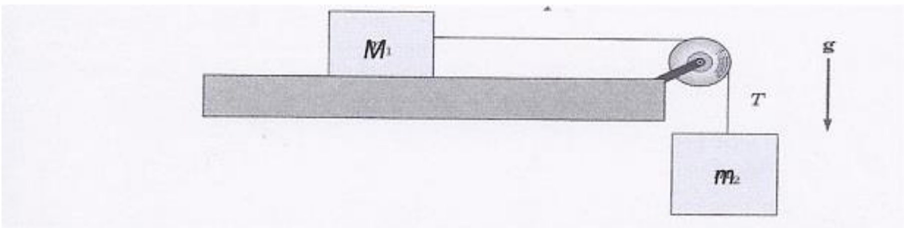


Figure 4.1 Glider of mass M on the horizontal board, connected by a string to mass m that falls vertically under the influence of gravity.

For a given mass M1 we can add more masses to m2 until the block starts moving. Then

$T = F_S$, $T = m_2g$, $F_n = m_1g$, $F_S = \mu_s F_n$. …………………………………… **Eq. 4.4**

Combining these equations to get

$m_2 = \mu_s M_1$ ……………………………………………………….. **Eq. 4.5**

Equation 4.5 can be used to calculate μ_s by determining the minimum mass m_2 that makes the block just move.

Similar calculations can be done when the block is moving in constant velocity (forces are in equilibrium)

m_2 = μ_k . M_1 ……………………………………………………………………

Eq. 4.6

When a block is placed over an inclined plane, as shown in Figure 4.2 whose angle is θ,

the normal force Fn acts perpendicularly to the plane, and the
component of the eight of the block (mg *cos* θ) acts in the opposite direction. Thus

F_n = mg *cos* θ_S ……………………………………………………… **Eq. 4.7**

Where θ_S is the angle at which the block starts to move down the plane.

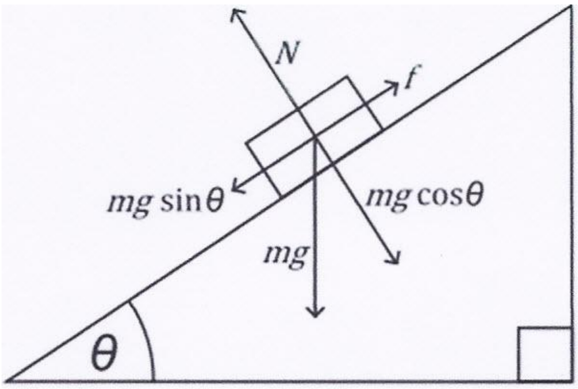


Figure 4.2 forces acting on a block on an inclined plane

The static frictional force will be equal to the weight component (mg *sin* Θ,) which acts down the plane:

F_s = mg sin θ_S ……………………………………………..…………….

Eq. 4.8

Combining Eq.4.7 and Eq. 4.8 we can calculate the coefficient of static friction

μ_s = mg *cos* θ_S/ mg *sin*θ_S = tan θ_S

Similarly an angle Θ_k can be determined when the block slides down the plane at constant velocity:

μ_k = tan Θ_k ………………………………………………………………

Eq. 4.9

Equation 4.9 can be used to calculate the coefficient of kinetic friction by measuring the angle Θ_k when the block slides down the plane in a constant velocity after it has been pushed slightly to start moving.

Pre-experiment questions

Read carefully the entire description of the experiment and answer the following questions:

1. What are the factors influencing the coefficient of static friction and the coefficient of kinetic friction.
2. The direction of a frictional force is always in (a) opposite to, or (b) the same direction of the motion of an object?
3. How does the coefficient of kinetic friction depend on the speed of a moving object?
4. What are the units of the coefficients of friction?

Materials & Equipment

Smooth wooden board with pulley attached to one end

Smooth wooden block with hook attached

Pulley with mounting clamp

Balance

String

Slotted Masses with holder

Procedure

Part One: Horizontal board with pulley

1. Determine the mass of the block M_1
2. Place the block in a horizontal position on the wooden board
3. Attach a piece of string to the hook in the block. Place it over the pulley and attach the mass holder to the other end of the string.
4. Carefully add masses to the mass holder to find the minimum mass needed to just the block to move. Record the value of the mass as m2 in the data table.
5. Repeat the procedure for two more times placing the block on different parts of the board.
6. Repeat step 4 and 5 with adding masses over the block with 200, 300, 400 and 500g respectively and record three trials. (static friction)
7. Perform a similar set of measurement in step 1 through 6, but determine the mass m2 needed to keep the block moving in a constant velocity after it has been started with

a small push. Again add masses to the block m1 and record the needed m2 (Kinetic friction).

8. Record your date in table 4.1 and 4.2
9. Perform a similar set of measurement in step 1 through 8 for another block

$M_1\ (gm)$	$m_2\ (gm)$			$\overline{m_2}\ (gm)$
	1	2	3	

Figure 4.1 static friction

$M_1\ (gm)$	$m_2\ (gm)$			$\overline{m_2}\ (gm)$
	1	2	3	

Figure 4.2 Kinetic friction

Part Two: Inclined Plane

1. Place the block with its large surface on the plane and incline the plane until the board just starts to slide down. Record the angle as θ_S; in your date table
2. Repeat the procedure three more times to get 4 records of θ_S.
3. Repeat steps 1 and 2 but with an angle that the block moves down in a constant velocity. Record the angle as θ_k, try to use different parts of the board to average the effects of non-uniformity of the surface.
4. Record your date in table 4.3and 4.4
5. Perform a similar set of measurement in step 1 through 4 for another block

θ_s	$\mu_s = \tan\theta_s$

Figure 4.3 static friction

$\boldsymbol{\theta_k}$	$\boldsymbol{\mu_k} = \tan\theta_k$

Figure 4.4 kinetic friction

Calculations

1. Calculate the mean $\overline{m_2}$ for the three trials of m_2 for each value of m_1 for both static and kinetic cases.
2. Plot m_2 Vs. M_1 according to Eq. 4.5 and 4.6 to find the slope (equals to μ_s and μ_k).
3. For each θ_S calculate the coefficient of friction. Record the values in the calculation table. Calculate the mean value $\overline{\mu_s}$ and standard error α_{μ_S}.
4. Repeat step 1 for θ_k to calculate $\overline{\mu_k}$ and standard error α_{μ_k} .

Post-experiment Questions:

1. What is the ratio of the frictional force F to the applied force mg for each case? Is F small compared to the applied force in every case?
2. Discuss the disagreement between the two different values of μ_s for horizontal and inclined planes. Calculate the percentage difference between them.
3. Repeat step 2 for μ_k.
4. Do your data confirm that μ_s is greater than μ_k?

Experiment 5: Hooke's Law and Simple Harmonic Motion

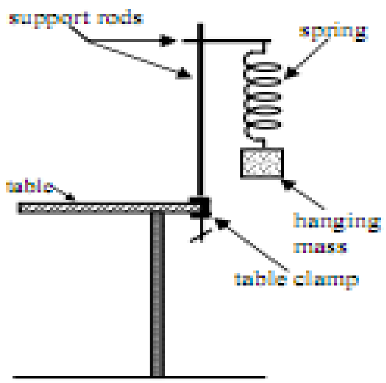
Objectives

1. To determine the force constant of a spring.
2. To study the motion of a spring and mass when vibrating under influence of gravity.

Theory

Most springs obey Hooke's Law, which states that the force exerted by the spring is proportional to the extension or compression of the spring from its equilibrium length.

$$F = -k.x \text{ --- Eq. 5.1}$$



k is called the spring constant and is a measure of the stiffness of the spring. The minus sign indicates that the direction of the force is opposite to the direction of the displacement. In the SI system, the units of spring constant k are N/m. The diagram shows a mass to the right of its equilibrium position($x = 0$). The displacement (of the mass is $(+)$ and the spring force is to the left $(-)$. If the spring is compressed, then x is $(-)$ and the spring force is $(+)$.

Simple harmonic motion occurs whenever there is a restoring force which is proportional to the displacement from equilibrium, as is the case here. Assuming no frictional forces and assuming that the spring is massless, the equation of motion $(ma = F)$ of a mass on a spring is

$$m\frac{d^2x}{dt^2} = -k.x \quad or \quad \frac{d^2x}{dt^2} = -\frac{k}{m}x \text{ ------------------------------- } \textbf{Eq. 5.2}$$

The solution of this second-order differential equation is

$$x(t) = A\,sin(\omega t + \varphi) \qquad \omega = \sqrt{\frac{k}{m}} \text{ ----------------------------- } \textbf{Eq. 5.3}$$

where A and φ are constants which depend on the initial conditions, the initial position and initial velocity of the mass. The period$T$, the frequency f, and the constant ω are related by

$$\omega = 2\pi f = \frac{2\pi}{T} \text{ -- } \textbf{Eq. 5.4}$$

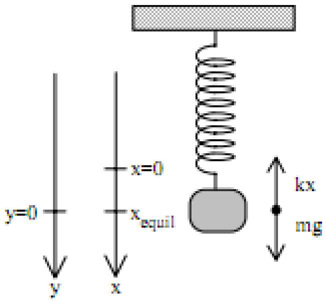
Thus the period T is given by

$$T = 2\pi\sqrt{\frac{m}{k}} \text{ --- } \textbf{Eq. 5.5}$$

A very important property of simple harmonic motion is that the period T does not depend on the amplitude of the motion, A

If the mass is hung from a vertical spring, it will still execute simple harmonic motion with the same period (5), as we will now show. When the mass is hung from the spring, the spring is stretched from its equilibrium length by the weight mg of the mass. The equilibrium displacement of the mass under the influence of the force of gravity (down) and the force from the spring (up) is $x_{equil} = \frac{mg}{k}$

Now that there are two forces acting on the mass, the equation of motion becomes



$$\boldsymbol{m\frac{d^2x}{dt^2} = mg - kx}$$ ---------------------------------------

Eq. 5.6

We now perform a change of variable by introducing a new coordinate $y = x - \frac{mg}{k}$,

Since $\frac{mg}{k}$ is a constant, differentiating y twice produces $\frac{d^2y}{dt^2} = \frac{d^2x}{dt^2}$. Also, $mg - kx = -ky$, therefore $eq. 6$ becomes

$$\boldsymbol{m\frac{d^2y}{dt^2} = -k.y}$$ ---

Eq. 5.7

which is exactly the same as $eq. 2$ except we have changed the name of the position coordinate from x to y. Since the equation of motion is the same, the solution is the same for eq.3, with the same period in the eq.5.

A real spring has mass, a fact which we have ignored so far. A mass m on a real spring with mass m_{spring} oscillates more slowly than predicted by eq.5, since the spring has to push its own mass about as well as the mass m. However, the theoretical expression of eq.5 can be corrected by replacing the mass m with an *effective mass* (m_{eff}), consisting of m plus some fraction of m_{spring}

$$\boldsymbol{m_{\text{eff}} = m + \text{f}.m_{\text{spring}}}$$ ------------------------------------**Eq. 5.8**

where f is some fraction ($\text{f} < 1$), which depends on the exact shape of the spring. [Although f can be computed, the computation is rather complicated and depends on the precise shape of the spring.]

In this experiment, you will first determine the spring constant k of a spring, by hanging various weights from the spring and measuring the extension. Then, you will measure the period of oscillation of a mass m hanging from the spring, and will compare this measured period with period predicted by $eq. 5$ [with m_{eff} used instead of m].

Finally, you will repeat your measurement of the period with two other masses and check that the period is proportional to $\sqrt{m_{\text{eff}}}$.

Pre-lab questions

1. What condition or conditions are necessary for simple harmonic motion to occur?
2. What are the units of the spring constant k in SI units, which are also called MKS units (MKS = **M**eter-**K**ilogram-**S**econds)? What are the units in the c.g.s system (centimeter-gram-second)?
3. Where in the complete up-and-down period does the mass on the spring have the greatest and least speeds? Where does it have the greatest and least velocities?

Materials & Equipment

Set of coil springs

Slotted Weights & Weight hanger

Weight hanger

Hooke's Law Apparatus (modified meter stick)

Support stand with clamps,

Lab timer / Stopwatch

Lab balance.

Procedure and Calculation

Part 1: Measurement of the spring constant k

Begin by weighing the spring (you will need the weight in part 2). You might want to check the reliability of the digital balances by weighing the spring on two different balances. The spring used in this lab has a tapered coil which serves to reduce the interference of the windings with each other and make the spring behave more like a perfect Hooke's spring. Always hang the spring with the larger windings downward.

With the empty mass tray hanging from the spring, measure the position of an edge of the tray. This will be the zero position, which you will subtract from all subsequent positions. There is a mirror by the meter stick scale so you can avoid parallax when you measure positions. Now add the slotted weights to the tray, one at a time, and measure the positions of the same edge as each mass is added. Add masses in 50 gram increments to a total of 500 grams: $\Delta\mathrm{m} = 50\mathrm{g}, 100\mathrm{g}, 150\mathrm{g}, \ldots$ Use the balance to check that the masses are accurate.

Plot the weight added ($\Delta m. g$) vs. Δx , the position change from the *zero position*. Use the known value of $g = 9.796\, m/s^2$. This graph should be a straight line with slope k.

To determine the slope, compute $k = -\frac{\Delta m\,.\,g}{\Delta x}$ for each data point, and compute the mean, the standard deviation, and the standard deviation of the mean of your several k values.

$$\boldsymbol{k_{avg}} = \frac{1}{N}\sum_{i=1}^{N} \boldsymbol{k_i} \qquad \sigma = \sqrt{\frac{\sum_{i=1}^{N}(k_i - k_{avg})^2}{N-1}} \qquad \sigma_{mean} = \frac{\sigma}{\sqrt{N}}$$

[Side comment: You might think to determine the best value of k by measuring the slope of ($\Delta m.g$) vs. Δx , using the "slope" function in Excel. This is not quite right since what we want is the best fit line which goes through the origin, while the slope function finds the slope of the best fit line, which, in general, has a none-zero intercept.]

Part 2: Measurement of the period

Remove the weight tray from the spring and load the spring with a 100 gram mass with a hook. Carefully, set the mass oscillating with a small amplitude motion and use a stop watch to time the interval for several complete oscillations. If the time for N complete periods ($\mathrm{N} \approx 50$ or more) is $\mathrm{T_{total}}$, then the period is $\mathrm{T_{meas}} = \frac{\mathrm{T_{total}}}{\mathrm{N}}$. By measuring the time for many periods, the uncertainty in T, due to your reaction time, is reduced by a factor of N.

$\delta\mathrm{T_{total}}$ =Human reaction time ≈ 0.1 sec. $\delta\mathrm{T} = \frac{\delta\mathrm{T_{total}}}{\mathrm{N}}$.

[DO NOT measures one period 50 times; measure the time for 50 periods, once.]

If you have time, repeat this measurement at least once, to check the reproducibility of this method.

Now compute the period using eq'n (5) with $\mathrm{m_{eff}}$ in place of m

$$\mathbf{T_{calc}} = \mathbf{2\pi}\sqrt{\frac{\mathbf{m_{eff}}}{\mathbf{k}}} \qquad \text{---}$$

Eq. 5.9

Also compute $\mathrm{T_{calc}}$, the uncertainty in $\mathrm{T_{calc}}$. Compare the calculated and measured periods.

Repeat this procedure with $\mathrm{m} = 200\mathrm{g}$ and $\mathrm{m} = 500\mathrm{g}$. Make a plot of $\mathrm{T_{meas}}$ vs. $2\pi\sqrt{\frac{\mathrm{m_{eff}}}{\mathrm{k}}}$, using your three data points. On the same graph, plot the line $\mathrm{y} = \mathrm{x}$. Finally, compute the quantity $\mathrm{R} = \frac{\mathrm{T_{meas}}}{\mathrm{T_{calc}}}$ for each of your three data points. Do theory and experiment agree?

Post-lab Questions:

4. A given spring stretches 15 cm when it is loaded with a 250 gram weight. What is the spring constant of the spring?
5. Sketch the graph $(\Delta m.g)$ vs. Δx for a mass on a spring. Indicate the slope and intercept.
6. What happens to the period of a mass-on-a-spring simple harmonic oscillator if the mass is doubled? What happens to the period if the spring constant is reduced by a factor of 3? How does the period depend on the amplitude of the oscillation?
7. True or False: for a simple harmonic oscillator consisting of a mass on a spring, the period measured when the mass is hanging vertically is different than the period measured when the spring and mass are supported horizontally..
8. Show with a sketch what a graph of T^2 vs. $\frac{m_{\text{eff}}}{k}$ looks like. What are the slope and intercept?
9. Assuming that k,m_{eff}, δk, and δm_{eff} are known, show how to compute $\delta \mathrm{T}_{\text{calc}}$,where T_{calc} is given in eqn (9).
10. A mass m hanging from a spring with spring constant k is taken to the Mars, where g is 1/3 of its value on Earth, and the period of the oscillation is measured. Is the measured period on the Mars the same as the period measured on the Earth? Explain your answer.

$m\ (kg)$	$d\ (m)$	$f = mg\ (N)$	$K = \frac{f}{d}(\frac{N}{m})$

$M\ (kg)$	$T\ (sec) for\ 20\ complete\ oscillations$	$T_{ave}/20$	$T_{calculated}$	R

	T_1	T_2	T_3	$= \boldsymbol{T}_{\boldsymbol{measure}}$		$= \frac{\boldsymbol{T}_{\boldsymbol{meas}}}{\boldsymbol{T}_{\boldsymbol{calc}}}$

Experiment 6: Work, Energy and Centripetal Force

Objectives

Determine the acceleration of an object undergoing uniform circular motion.

- Use position, velocity, acceleration and force as vector quantities.
- Use forces to make quantitative predictions for objects in circular Motion

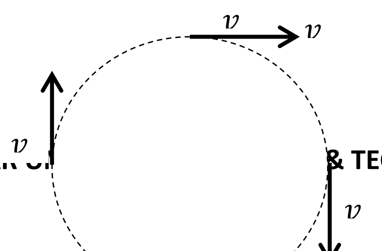
Theory

When an object moves in a circle at constant speed the velocity vector of the object's motion is always tangent to the circle. This implies that the direction of the velocity is continuously changing, and thus the object is accelerated because acceleration is by definition a change in velocity per unit time. Figure 6.1 shows the velocity vector at various points around the circle for an object moving in a circle at constant speed. The lengths of the vectors are the same because the speed is constant, and the direction of the vectors indicates the direction of the velocity at that point. Also shown in Figure 6.1 are the velocity v_i and v_f at two times t_i and t_f with a very short time interval between them. In the third part of the figure is shown the vector difference,

$$\boldsymbol{\Delta v} = \boldsymbol{v_f} - \boldsymbol{v_i} \quad \text{……………………………………………………} \quad \textbf{Eq. 6.1}$$

indicating that the change in velocity Δv always points toward the center of the circle. The acceleration a is defined by

$$\boldsymbol{a} = \frac{\boldsymbol{\Delta v}}{\boldsymbol{\Delta t}} \quad \text{……………………………………………………………} \quad \textbf{Eq. 6.2}$$



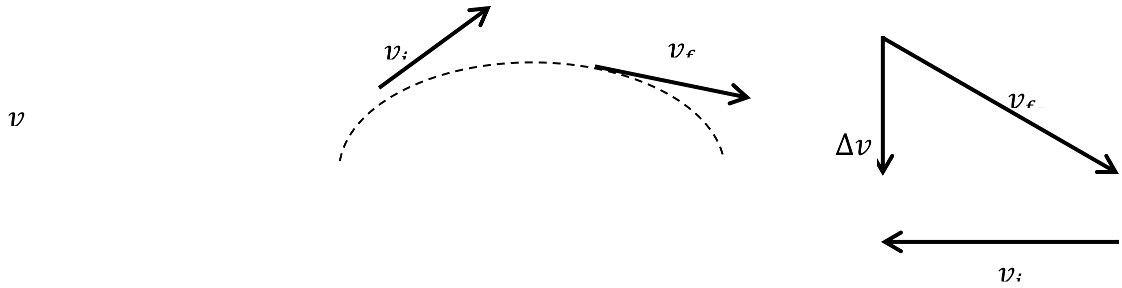


Fig. 6.1 Velocity vectors for circular motion at constant speed.

Thus the acceleration is in the direction of Δv and is always pointed toward the center of the circle. The magnitude of the acceleration a is given by

$$\boldsymbol{a = \frac{v^2}{R}}$$ ………………………………………………………………… **Eq. 6.3**

According to newton's second law the magnitude of the centripetal force F and the magnitude of the centripetal acceleration a are related by $F = Ma$,

Where M is the mass of the object moving in a circle at constant speed v. Therefore, using equation 6.3 for the acceleration gives

$$\boldsymbol{F = M\frac{v^2}{R}}$$ …………………………………………………………………

Eq. 6.4

If the object moves at constant speed v in a circle of radius R, the time of one complete revolution around the circle is the period T. Then, v can be expressed in terms of time T as follows:

$$\boldsymbol{v = \frac{2\pi R}{T}}$$ ……………………………………………………………………

Eq. 6.5

The centripetal force can also be expressed in terms of the angular velocity ω or frequency of rotation, f, by using the expressions $v = R\omega$ and $\omega = 2\pi f$.

$$\boldsymbol{F = M\frac{v^2}{R} = M\frac{(R\omega)^2}{R} = MR\omega^2}$$ ……………………………………….

Eq. 6.6

And

$$F = MR(2\pi f)^2 = 4\pi^2 MRf^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

Eq. 6.7

where ω is in units of radians per second and f is in hertz (cycles per second). It is the usual convention in rotational motion to think of f as being in revolutions per second.

In this laboratory independent measurements of the quantities F, M, v and R will be made to verify these relationships.

Centripetal force Apparatus

The centripetal force apparatus has a mass bob with a pointed tip at the bottom that is suspended from a horizontal rotating bar. The bob also has a spring hooked between the side of the bob and the central rotating shaft in such a way that the spring provides a horizontal centripetal force when the bob rotates in a horizontal plane. The bob is rotated at a fixed radius R from the central rotating shaft by ensuring that the tip of the bob passes on each revolution precisely over a pointer located a distance R from the central rotating shaft. For a given mass M of the bob and a particular spring, the bob will rotate at a given radius R only for one particular rotation period T. Figure 6.2(a) shows the apparatus when the system is rotating at the period necessary to produce a rotation at radius R. A measurement of T will be made for a given R and M. equation 5.5 allows a determination of v, and using that value in equation 6.4 allows the determination of the centripetal force F. This will be referred to as F_{theo} for the theoretical value of the force.

The force F depends on the amount the spring is stretched when the bob is rotating. The value of this force can be measured by determining the force needed to stretch the spring by the same amount when the apparatus is not rotating. Figure 6.2(b) shows how a string can be attached to the other side of the bob ad slotted masses can be applied over the pulley mounted near the end of the base. The weight of the total mass needed to stretch the spring until the tip of the bob is aligned with the pointer, is the experimental value of the centripetal force$F$. This will be referred to as F_{exp}.

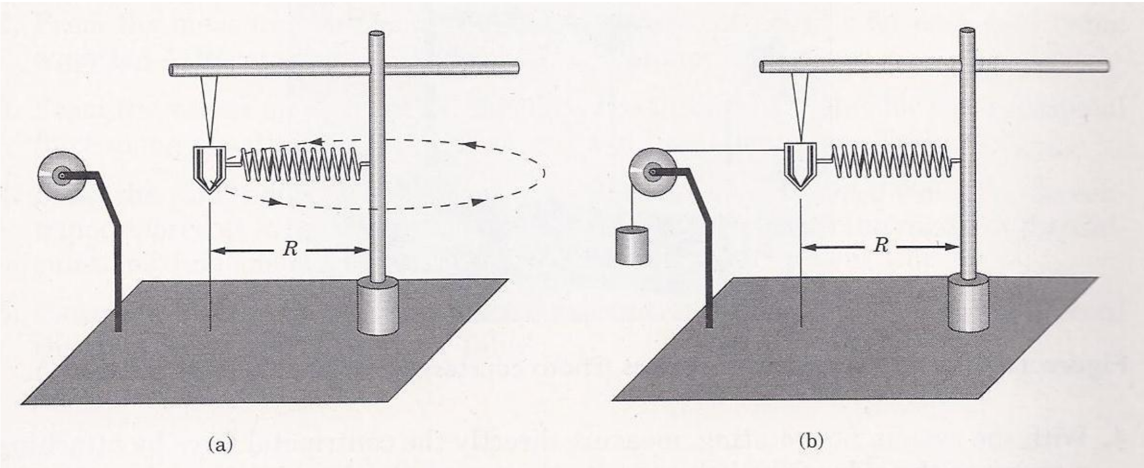


Figure 6.2 (a) Centripetal force apparatus rotating. (b) determination of the centripetal force by measuring the force needed to stretch the spring under static conditions.

Pre-lab questions

1. How does the force required to keep an object rotating at a constant speed change depending on the object's rotational period?
1. How does the period of a rotating object depend on its mass when the force exerted on it and its radius of rotation is kept constant?

Materials & Equipment

Lab timer or stopwatch
Metal ruler
Weight Hanger & Slotted weights
Strings
Laboratory balance
Centripetal Force Apparatus
Vernier caliper
Safety glasses

Procedure

1. Detach the bob from the apparatus and find its mass with a lab balance (without the spring). Record the value as M_b in the Data Table. Reattach the bob to the string on the horizontal support arm and attach the spring as well.
2. Carefully adjust the position of the vertical pointer rod to line up vertically with the point on the end of the rotating bob and measure the distance (from the pointer tip and the center of the vertical rotor shaft). You will leave the pointer rod in this position for the rest of the experiment.
3. Rotate the system as shown in figure 6.2 (b) by twirling the rotating shaft between your thumb and first finger. Measure the amount of time for the bob to make 25 rotations, with one student operating the lab timer and a second student counting off the rotations. This will be $Time1$. Note: make sure you are comfortable with the procedure for rotating the bob and making the measurement before you record your measurements.
4. Repeat the counting-timing procedure two more times. Record the time as $Time2 \; and \; Time3$. Find the time T by dividing the average time the apparatus took to make the 25 rotations by 25 (in seconds).
5. Attach a string to the bob opposite the spring and suspend a weight hanger over the pulley. Add slotted weights to the hanger until the bob is directly over the pointer. Record the mass as M_a, including the mass of the weight hanger.
6. Repeat steps 3-5 by having the same radius R but adding more masses on the top of the bob. First add 0.05 kg, the total mass M_b will be (bob mass + 0.05)kg. Perform all measurements and record in the Data Table. Then repeat for 0.10 kg mass to be added on the top of the bob.

7. Remove the slotted mass from the bob, use the bob as the rotating mass but with three different values of rotation radius R. Repeat steps 3-5 and record your measurements in the Data Sheet (table 2).

Table 1. Data of Centripetal force measurements when R is constant

$M\ (kg)$	$T\ (sec) for\ 25\ complete\ oscillations$			$T_{ave}/25 = T$	$F_{theory} = M\frac{4\pi^2 R}{T^2}$ (N)	m (kg)	$F_{exp.} = mg$
	T_1	T_2	T_3				

Table 2. Data of Centripetal force measurements when M is constant

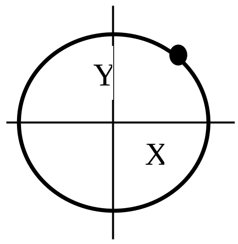
$R\ (m)$	$T\ (sec) for\ 25\ complete\ oscillations$			$T_{ave}/25 = T$	$F_{theory} = M\frac{4\pi^2 R}{T^2}$ (N)	m (kg)	$F_{exp.} = mg$
	T_1	T_2	T_3				

Calculations

1. For the first part of the experiment, calculate the mean of three trials of the Time, record in the Calculations Table and find the rotation period T.
2. Calculate the speed of rotation of the bob, using the data and equation 6.5 where $2\pi R$ is the circumference of the circular orbit and T is the average time per revolution.
3. Then calculate the theoretical value of the centripetal force F_{theo} using Eq.6.4.
4. From the values of M_a for each case, calculate the experimental value for the centripetal force as $M_a g$. Use a value of 9.8 m/s^2 for g. Record the result in the Calculations Table as F_{exp}. Compare this value with the calculated value and compute the percentage difference between the two results.

Post-lab Questions:

1. Do your experimental results confirm the relationship for the centripetal force given by $F = Mv^2/R$? Consider the agreement between F_{theo} and F_{exp}.
2. What are the limitations on the accuracy of your measurement?
3. A ball on the end of a string travels in a clockwise circle at constant speed. On the figure at right, draw the vectors requested below, label them clearly, and explain your choices.
   a) The position vector for the ball.
   b) The velocity vector for the ball.
   c) The acceleration vector for the ball.



Experiment 7: Static Equilibrium of Rigid Bodies: Torques

Objectives

1. To examine mechanical equilibrium and torque and how it applies to rigid bodies.

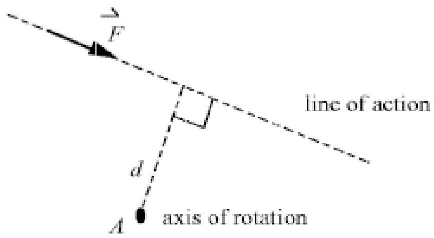
Theory

In order for a rigid body to remain in equilibrium, the following two conditions must be satisfied:

1. The resultant external force acting on the body must be zero.
2. The sum of the moments (torques) acting in a counter-clockwise direction about any point must equal the sum of the clockwise moments about the same point. (**Principle of Moments**).

The body is in **static** equilibrium if it is at rest with respect to its frame of reference (which in this case would be the lab table).

The **moment of a force**, or **torque**, is a measure of the force's tendency to cause rotation. It is defined as *the product of the magnitude of the force and the perpendicular distance from the axis of rotation to the line of action of the force*. In the case of a lever, the axis of rotation is called the **fulcrum**.



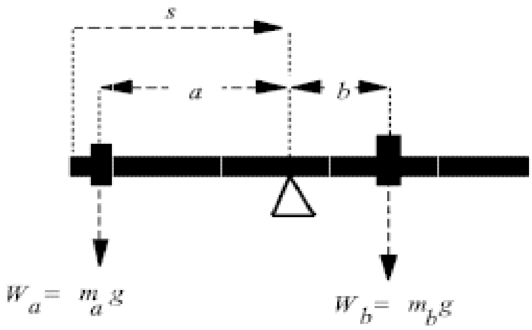
Definition of Torque

The moment of force, $\vec{F}$ about an axis of rotation through A is given by $F.d$. (Of course, the units of torque are those of force x distance).

Consider the system shown below. If the horizontal bar is a stick of uniform cross-section and density balanced at its center of mass, then this system is subjected to two torques about a point at the center of mass of the stick:

1. The force $W_a = m_a.g$ at perpendicular distance a counterclockwise.

2. The force $W_b = m_b.g$ at perpendicular distance b clockwise



The second condition of static equilibrium (The Principle of Moments) is satisfied if

$$\mathbf{W_a.a = W_b.b}$$ -- **Eq. 7.1**

this simplifies to

$$\mathbf{m_a.a = m_b.b}$$ -- **Eq. 7.2**

Materials & Equipment

A Uniform and a non-uniform meter sticks

3 meter stick clamps with knife-edge

Load supports

A 2 kg range spring scale

A set of hooked weights

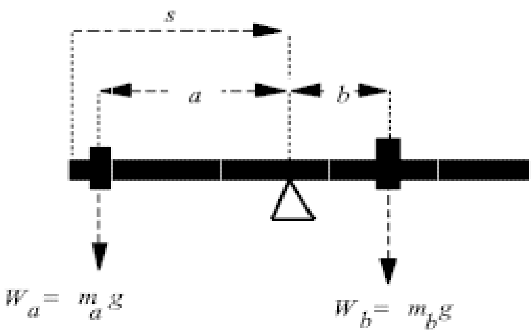
A laboratory balance and a support stand.

Procedure and Calculations

A. Testing the Principle of Moments

1. Place one meter stick clamp near the center of the uniform meter stick and suspend this combination from the suspension point mentioned above so that the zero cm mark of the meter stick is at the left end.
2. Find the center of mass of the meter stick by sliding it in its clamp until it lies horizontally at rest; record this position, s.
3. Weigh the two clamps and record their masses.

4. With the meter stick as above, suspend a weight from a hanger on each side of the center of mass, as shown in the figure below. Use $m_b \geq 2\, m_a$ so that you get very different distances for a and b.
5. Record your data in table 1 and verifying the sum of torques is equal to zero



$\tau_{cw}(\mathrm{N.m})$			$\tau_{ccw}(\mathrm{N.m})$			
$M\ (kg)$	$W = Mg\ (N)$	$r\ (m)$	$m\ (kg)$	$W = mg\ (N)$	$r\ (m)$	$\frac{1}{r}(m^{-1})$

Table 1

B. The Non-Uniform Meter Stick

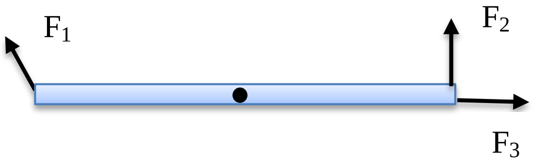
1. Set up the non-uniform meter stick set up exactly as in the previous setup. d, the distance from the zero end of the stick to the center of mass is unknown
2. Find d theoretically by using this equation $r_3 = \frac{(m_1 * r_1 + m_2 * r_2)}{m_3}$.
3. Measure d on the lab scale and compare it to the value calculated above.

$\tau 1_{cw}(\mathrm{N.m})$		$\tau 2_{cw}(\mathrm{N.m})$		$\tau_{ccw}(\mathrm{N.m})$	
$m_1\ (gm)$	$r_1\ (cm)$	$m_2\ (gm)$	$r_2\ (cm)$	$m_3\ (gm)$	$r_3\ (cm)$
known	**known**	**known**	**known**	**known**	**? ? ? ?**

Post-lab Questions:

1. A long stick is supported at its center and is acted on by three forces of *equal* magnitude, as shown at right. The stick is free to swing about its support. F2 is a vertical force and F3 is horizontal.

- Rank the magnitudes of the torques exerted by the three forces about an axis perpendicular to the drawing at the *left* end of the stick. Explain your reasoning.
- Rank the magnitudes of the torques about the *center* support. Explain your reasoning.
- Rank the magnitudes of the torques about an axis perpendicular to the drawing at the *right* end of the stick. Explain your reasoning.
- Can the stick be in translational equilibrium? Explain your reasoning.
- Can the stick be in rotational equilibrium? Explain your reasoning.



Experiment 8: Simple Harmonic motion: The Pendulum

Objectives

1. To study systems undergoing simple harmonic motion,
2. Measure the amplitude and period of a pendulum motion,
3. To find out how the period of a pendulum movement depends on its length and mass, and on the amplitude of its swing, and
4. To learn how to read and represent frequency, period, amplitude, and phase on a graph.

Theory

Objects generally have two kinds of motion. One kind of motion goes from one place to another like a person walking from home to school. This is *linear motion*. We use words such as distance, time, speed, and acceleration to describe linear motion. The second kind of motion repeats itself over and over like a child going back and forth on a swing. This kind of motion is called *harmonic motion*. The word *harmonic* comes from the word *harmony* meaning "multiples of." Any system that exhibits harmonic motion is called an *oscillator*.

The pendulum

The simple pendulum is an example of oscillator. It consists of an idealized body; a point mass suspended from a massless inextensible string swinging in a vertical plane solely under the influence of gravity. The mass is free to swing back and forth. A ***cycle*** is one complete back-and-forth motion. The ***period*** is the time it takes to complete one full cycle. The period of a pendulum is the time it takes for the pendulum to swing from left to right and back again. The ***amplitude*** describes the size of the cycle. The amplitude of a pendulum is the amount the pendulum swings away from equilibrium.

There are four fundamental physical properties of the pendulum:

- Length
- Mass
- Angle
- Period

We will choose the period, that is, the time for the pendulum to go back and forth once, to be the dependent variable, and set the other physical properties to be the independent variables. If the instructor so chooses, we may also study the other properties of the pendulum as well. The period, *T*, of a pendulum is expressed mathematically as:

$T = f(\text{m, L, A})$

The independent variables can strongly influence, weakly influence, or have no influence on the dependent variable. To scientifically determine the strength of the dependence, the independent variables are varied one at a time. If the varying of a physical quantity causes no variance of the dependent variable to within experimental error, then that measured physical quantity has no effect on the dependent variable. For example, if the mass of a physical pendulum is changed and the period is measured, then the data taken will produce a graph similar to the following graph (next page). In the graph on the next page the vertical bars are called error bars. They are the one standard deviation errors in the averages for each data point. The observation that the best-fit line is horizontal and lies within all the error bars is sufficient evidence to enable one to state that the period of the pendulum is independent of its mass.

To determine the dependence of the period of the pendulum on its initial angle and its length requires two independent sets of measurements. In the first set keep the length constant while the angle is varied; in the second set keep the angle constant while the length is varied.

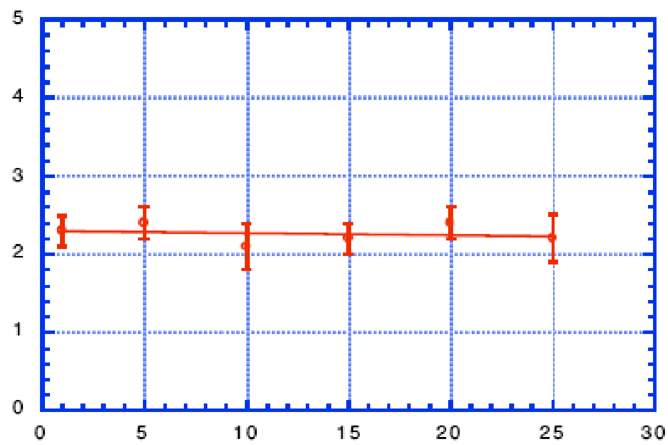


Fig. 8.1 Period of a pendulum as its mass changes.

The simple pendulum is shown in Figure 8.2. Let us suppose that at some point in the swing of a pendulum the string makes an angle *(A)* with the vertical. In that case, the forces on the point mass *m* are FT , the tension in the string, acting along the string, and mg, the weight of the pendulum acting straight down. Thus the resultant force acts along the trajectory of the mass and has a magnitude of *mg.sin(A)*. The trajectory of the mass is always perpendicular to the tension FT . As well, the distance *S* along the trajectory from the equilibrium position to the mass is equal to *LA* where *L* is the length of the string and *A* is measured in radians. There are many times in the study of physics when you will find out that approximations are made. This is done not because the physicist is lazy, but rather because such approximations make the final result simple and concise. Such approximations, however, place limitations on the system and can only be used if such limitations are acceptable.

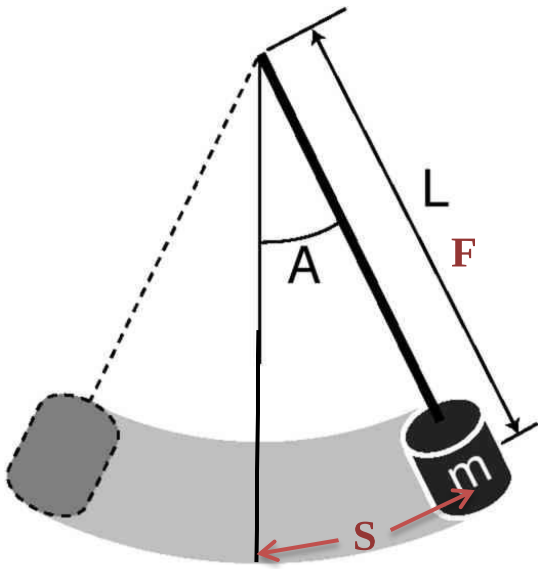


Fig. 8.2 Simple Pendulum

In this experiment we are going to make the approximation

$$A \cong \sin(A) \quad \text{..} \quad \textbf{Eq.8.1}$$

This is called the small angle approximation and is true for small values of A. In this case the restoring force is

$$F = -mgsin(A) \approx -mgA = -mg\frac{S}{L} = -\frac{mg}{L}S$$ ……………….. **Eq.8.2**

Using the fact that *F* = *ma* we get

$$a = -\frac{g}{L}S$$ …………………………………………………… **Eq.8.3**

Equation 8.3 above is the equation of motion for the pendulum bob. It states that the acceleration *a* of the bob along the circular path is directly proportional but opposite in direction to its displacement *S* from the rest position. This is the condition for the simple harmonic motion SHM, and in this case

$$\omega = \sqrt{\frac{g}{L}}$$ …………………………………………………… **Eq.8.4**

and so

$$T = 2\pi\sqrt{\frac{L}{g}}$$ ……………………………………………………**Eq. 8.5**

Where ω is called the angular frequency of the motion and is given in radians and *T* is the period of the oscillation.

Pre-lab questions

1. How do we describe the back-and-forth motion of a pendulum?
2. If mass does not affect the period, why is it important that the pendulum in a clock be heavy?

Materials & Equipment

Ballistic pendulum apparatus with projectile ball

Laboratory balance and calibrated masses

Hooked metal balls or slotted masses

Rod and Base

Meter stick

Stopwatch or Lab Timer

String

Procedure

Part I

1. Attach a string to the pendulum clamp mounted on the provided stand. Ensure that you understand where the pivot point is.
2. Use the following set of length and record the time for 25 oscillation when the amplitude is 10°.
3. Record your data in table 1
4. Plot the graph between L and T with constant amplitude
5. Find gravitational acceleration (g).

L (m)	Time for 20 oscillations			$T = \frac{T_{avg}}{20}$	$T^2(sec$
	T_1 (sec)	T_2 (sec)	T_3 (sec)		
1					
0.9					
0.8					
0.7					
0.6					
0.5					
0.4					
0.3					
0.2					

0.1					

Part II

1. Fix the length of the string at 40 cm
2. Use the following set of angles (10°, 15°, 20°, 30°, 45°, and 60°) for timing the period. When timing the period, greater accuracy can be obtained by timing for 25 periods and dividing the result by 25.
3. Record your data as in table 2
4. Plot the graph between amplitude and period.

θ	Time for 20 oscillations			$T = \frac{T_{avg}}{20}$
	T_1 (sec)	T_2 (sec)	T_3 (sec)	
$10°$				
$15°$				
$20°$				
$25°$				
$30°$				
$35°$				
$40°$				

Table 2

Part III

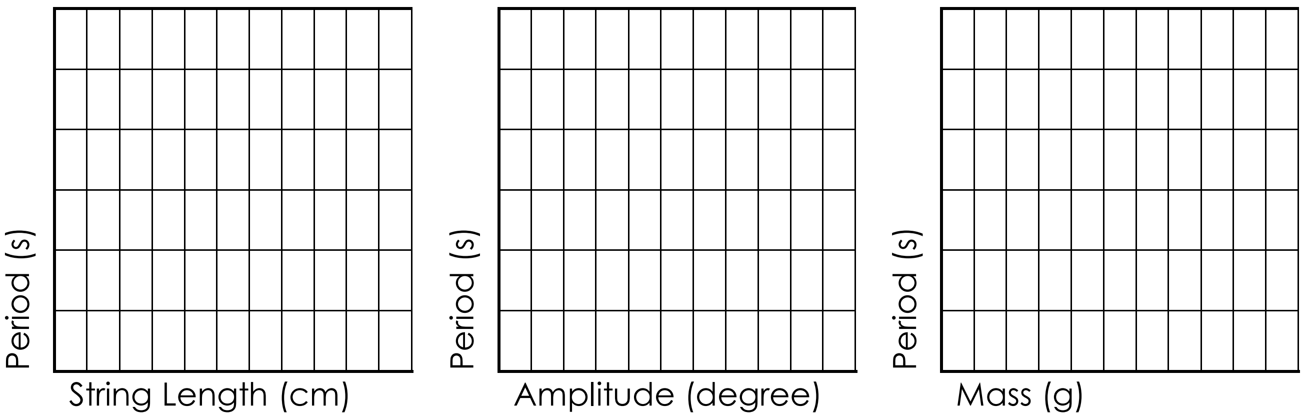
At an angle of 15° and length of 50 cm, measure the period of the pendulum for two different masses of the bob and record your data in table 3.

$m\ (gm)$	Time for 20 oscillations			$T = \frac{T_{avg}}{20}$
	T_1 (sec)	T_2 (sec)	T_3 (sec)	

Data Analysis

Your experiment should provide enough data to show that one of the three variables has much greater effect than the other two. Be sure to use a technique that gives you consistent results. Of the three things you can change (length, mass, and angle), which one has the biggest effect on the pendulum, and why? In your answer, you should consider how gravity accelerates objects of different mass.

Split up your data so that you can look at the effect of each variable by making a separate graph showing how each one affects the period. To make comparison easier, make sure all the graphs have the same scale on the *y*-axis (period). The graphs should be labeled as shown in the example below:



1. Make a graph of period versus angle, with the one standard deviation error bars displayed for the error in the period. Does your data show that the period has a dependence on angle? Why?
2. Make a graph of period versus length, with the one standard deviation error bars displayed for the period. Does your data show that the period has a dependence on length? Why? What sort of dependence?

3. Make a graph of period versus mass, with the one standard deviation error bars displayed for the period. Does your data show that the period has a dependence on mass? Why?

Bonus: Show that: $T \propto \sqrt{L}$ using a graphical method.

Experiment 9: Liquid Mechanics - Buoyancy

Objectives

1. Investigate the concept of buoyancy and the forces acting on an object immersed in a liquid,
2. Define Archimedes' Principle, and how to use it to measure specific gravity of objects and liquids, and
3. Investigate the dependence of buoyant force value on the density of the object and density of the liquid and the volume of an object immersed in a liquid.

Theory

In physics, **buoyancy** is a force exerted by a liquid, gas or other fluid that opposes an object's weight. In a column of fluid, pressure increases with depth as a result of the weight of the overlying fluid. Thus a column of fluid, or an object submerged in the fluid, experiences greater pressure at the bottom of the column than at the top. This difference in pressure results in a net force that tends to accelerate an object upwards. The magnitude of that force is proportional to the difference in the pressure between the top and the bottom of the column, and is also equivalent to the weight of the fluid that would otherwise occupy the column. For this reason, an object whose density is greater than that of the fluid in which it is submerged tends to sink. If the object is either less dense than the liquid or is shaped appropriately (as in a boat), the force can keep the object afloat. This can occur only in a reference frame which either has a gravitational field or is accelerating due to a force other than gravity defining a "downward" direction (that is, a non-inertial reference frame). In a situation of fluid statics, the net upward force on the object is called ***Buoyant Force***. The **size** of the buoyant force was discovered by Archimedes to be exactly equal to the **weight** of the fluid d**isplaced** by the object.

In this experiment, we will use Archimedes' Principle to determine the specific gravity (and also the density) of: 1) a solid which is heavier than water, 2) a solid which is lighter than water, and 3) a fluid which is not water.

Archimedes' Principle

Archimedes' Principle states that ***the apparent loss of weight of a body immersed in a fluid is equal to the weight of the fluid displaced.*** This means that the difference in weight of an object when it is weighed in air and then weighed while submerged in a liquid is equal to the weight of the amount of liquid which would occupy the same volume as the object. Let's specialize to water as our liquid since we know that water has a density of $\rho = 1 g/cm^3$.

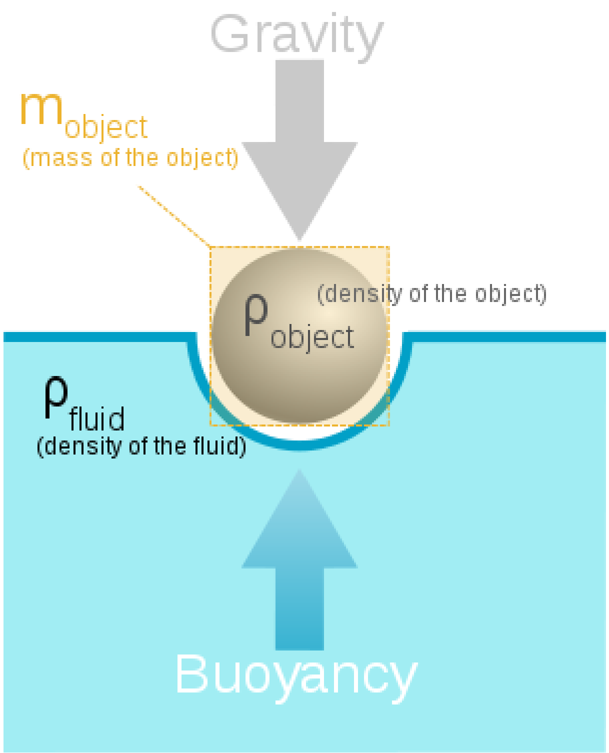


Fig. 9.1 Buoyancy Force

If the weight in air of an object which has a volume V is W, and the weight in water is W1, then the difference in weights will give the weight of an equivalent volume of water:

$$W - W_1 = W_{H2O} \text{ -- } \textbf{Eq.9.1}$$

Thus, the specific gravity (S) of the object can be found to be:

$$S = \frac{W}{W - W_1} \text{ -- } \textbf{Eq.9.2}$$

Since

$$\rho = \frac{W}{V}, \rho_W = \frac{W_{H2O}}{V} \text{ -- } \textbf{Eq.9.3}$$

And

$$S = \frac{\rho}{\rho_{H2O}} = \frac{W/V}{W_{H_2O}/V} = \frac{W}{W_{H_2O}} = \frac{W}{W - W_1} \text{ --------------------------- } \textbf{Eq.9.4}$$

To find the specific gravity of a liquid other than water, weigh an object submerged in the liquid. This weight will be called W2, and so W −W2 is the weight of a volume V of the liquid. Following the same argument as above, it can be shown that the specific gravity of the liquid is:

$$S = \frac{W - W_2}{W - W_1} \text{ .... } \textbf{Eq. 9.5}$$

Finally, to find the specific gravity of an object which floats in water, we cannot simply weigh it in water (since it will not completely submerge). Therefore, we have to tie a sinker to the object to keep it submerged but we also then have to be sure to subtract off the weight of the sinker. To do this, we first weigh the object with the sinker attached, but arrange it so that the object is out of the water and the sinker is completely submerged. This weight we call W_3 . Next, we weigh the object with the sinker attached while both are submerged. This weight is W_4. Now, W_3 is the weight of the object in air plus the weight of the sinker in water, and W 4 is the weight of the object in water plus the weight of the sinker in water. The weight of the sinker in water cancels out when these two weights are subtracted, so the weight of an equivalent volume of water is simply:

$$W3 - W4 = WH2O \text{ -- } \textbf{Eq. 9.6}$$

And the specific gravity of the object is:

$$S = \frac{W_0}{W_3 - W_4}$$ --

Eq. 9.7

Pre-lab questions

Prior to performing this experiment, write a hypothesis to address each of the following questions:

1. How does changing the volume of an object that is submerged in a fluid affect the buoyant force on the object.
2. How does changing the density of the object that is immersed in a fluid of constant density affect the buoyant force on that object.
3. How does changing the density of the fluid in which an object of constant density is immersed affect the buoyant force on the object.

Materials & Equipment

Set of metal cylinders

Wooden cylinder, 5 cm

Aluminum rod

Spring balance

Cylinders, 100 mL

Beaker 250 mL

Toluene, Vinegar, and salt water, 250 mL each

Procedure

For this experiment, we will determine the buoyant force by measuring the "weight" of an object in air, and then measure the "weight" when it is immersed in the fluid. The difference in these two "weight" readings will be taken as the upward force acting on the object in the given situation. You will examine the factors that determine the buoyant force acting on an object.

Part I: Object Density

1. Weigh a metal cylinder or ball in air. Record this as W.

2. Weigh the metal cylinder in water by immersing it in a 100 mL cylinder filled with 70 mL water. Do not let the object touch the bottom of the cylinder. Record this as W1.
3. Repeat steps 1 and 2 for different metal objects.
4. Be sure that you record the force (weight) reading to the nearest 0.01 N.
5. Be sure to thoroughly rinse and dry each metal object, beaker and graduated cylinder when you have finished using it.

Calculations and Graphing

1. Calculate the buoyant force for each metal object according to Eq.9.1
2. Calculate the specific gravity of the objects as in Eq. 9.2, along with uncertainties.
3. Plot the buoyant force vs. the density of objects
4. What is the mathematical relationship between buoyant force and density?
5. Explain why is it important not to allow the metal object to touch the cylinder bottom?

Part II: Liquid Density

In addition to water, the instructor will provide you with salt water, Toluene, Vinegar and one type of metal object.

1. Weigh the metal cylinder or ball in air. Record this as W.
2. Weigh the metal cylinder in water. Record this as W1.
3. Weigh the metal cylinder in other liquid. Record this as W2.
4. Repeat step 3 for the same object in different liquids.
5. Be sure that you record the force (weight) reading to the nearest 0.01 N.
6. Be sure to thoroughly rinse and dry the metal object, beaker and graduated cylinder when you change the liquid.
7. Return the Toluene to the stock bottle as instructed by lab assistant.

Calculations and Graphing

1. Calculate the buoyant force for each liquid according to Eq. 9.1.
2. Calculate the specific gravity of the liquids as in Eq. 9.5, along with uncertainties.
3. Plot the Buoyant force vs. for one rod in all three fluids.

4. How does the buoyant force appears to depend on liquid density? Derive a mathematical relationship.

Part III: Submerged Volume

1. Weigh a 10 cm Aluminum rod in air. Record this as W. Take its measurements.
2. Weigh the aluminum rod when only 3 cm of its length is immersed in water. Record this as W_1.
3. Repeat step 2 by increasing the depth of Aluminum rod in water by one cm each time.

Calculations and Graphing

1. Calculate the volume of displaced water for each volume of Al rod.
2. Calculate the buoyant force for each volume from equation 9.1
3. Plot Buoyant Force vs. Volume submerged for the Al rod in a given fluid.

Graphing

Each graph should have a legend which makes it clear which rod or fluid corresponds to each plot. Each graph should have a title which makes the parameters of that graph clear. When you have finished analyzing each of the graphs, you should be able to draw conclusions as to the relationship between:

a. Buoyant force and the density of the fluid in which it is submerged.
b. Buoyant force and the density of the rod that is submerged in a given fluid.
c. Buoyant force and the volume of fluid displaced.

Think about, discuss in your report, and make error calculations based on, the slope of each graph.

Experiment 10: Standing Waves

Objectives

Generate standing waves on a string, to demonstrate that the wavelength of these standing waves is proportional to the square root of the string tension, and to comprehend what is meant by a transverse wave. In so doing, a measurement of the frequency of oscillation of an electromechanical oscillator is made as well.

Theory

Waves are periodic disturbances propagating in space and time. We illustrate here properties of waves using waves in a stretched string and sound in an air column.

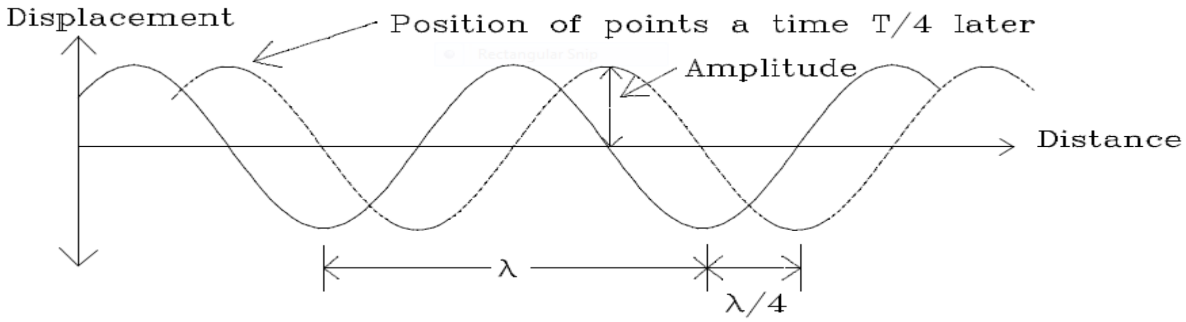
To be able to deal with waves we introduce a number of definitions:

- The **period** T is the time it takes until a wave repeats itself.
- The **frequency** f , defined as $f = 1/T$, measures the number of complete cycles the wave repeats in one second. The unit of frequency (1/seconds) is **Hertz** (Hz).
- The wavelength λ is the **spatial** separation between repeating points in a wave.
- The **amplitude** A of the wave is the maximum magnitude of the displacement.

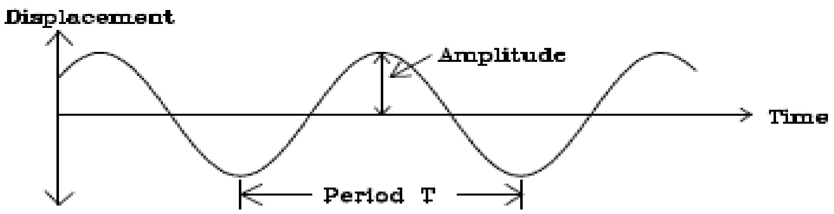
If a long, taut horizontal string is sharply pulled up at some point and released, this part of the string will vibrate up and down. Neighboring points will then follow the motion, and the original disturbance will propagate down the string as a "travelling wave". Since the individual particles vibrate in a direction perpendicular to the direction of propagation, the wave is called a transverse wave. If the disturbance is periodic, i.e., if the identical disturbance is repeated continuously, a wave train will move down the string. The following figure shows the disturbance along the string at a single instant of time. If the wave is moving to the right and a second picture is taken a quarter period $T/4$ later, all points on the wave will have moved an equal distance to the right, as shown by the dotted curve. The frequency (f)of the wave is defined as the number of times per second the disturbance is repeated. (Thus $f = 1 / T$). Note that the period of the motion is determined by the cause of the initializing disturbance. During each period T, the wave travels a distance of one wavelength λ; therefore the **velocity of the wave** is given by

$c = f.\lambda$

In which c will be a constant. But in general c could be a function of the frequency. (This effect is called dispersion)



The figure below shows the vertical displacement of the string versus time at a fixed location along the string. The time interval between successive identical displacements of a given point is the period T of the wave. Remember that the wavelength of a travelling wave can be determined only when one observes the displacement as a function of distance at one instant in time. The period, on the other hand, is obtained when one observes the displacement of one point as a function of time.



There are in general two possible types of waves: transverse and longitudinal waves. If something in the wave oscillates up and down or left and right (so the oscillation takes place perpendicular to the direction of propagation of the wave), the wave is transverse.

If a wave changes along the direction of propagation, it is called a longitudinal wave. (Such a wave clearly has only one polarization state.) Examples of longitudinal waves include sound waves, in which there are periodically changing regions of low and high air pressure along the direction of wave propagation

A sound wave is normally initiated by a vibrating solid (such as a tuning fork), which alternately compresses and rarefies the air adjacent to it. The wave thus consists of pressure variations in the air, moving away from the fork. Since these pressure and density variations oscillate back and forth along the direction of wave propagation, the sound wave is a longitudinal travelling wave.

The definitions of f , λ , and T (made above for a transverse wave) hold equally for a longitudinal wave. The diagrams in the above figures also apply, so long as we understand "displacement" to mean the longitudinal (i.e., forward or backward) pressure or density variation of air from its undisturbed equilibrium value. The relationship between wave velocity and the other parameters is also still valid:

$c = f.\lambda$

Standing Waves

So far we have considered only very simple wave disturbances. More complicated waves are created when two or more travelling disturbances are present simultaneously in the same medium. In general, any number of waves can be combined to give a more complicated wave.

A particularly interesting example occurs when two waves of equal λ ,f, and A are travelling along a taut string in opposite directions. (This occurs for example if the wave encounters a barrier, which reflects the wave back in the original direction with the original wave still propagating.) At some particular points on the string, the two waves will always be out of phase, i.e., one wave will try to move the point up and other wave will try to move the point down. The result is that the two waves will cancel each other at this particular point, and so that point will remain stationary. This condition is known as **destructive interference**, and the points at which this occurs are called **nodes**.

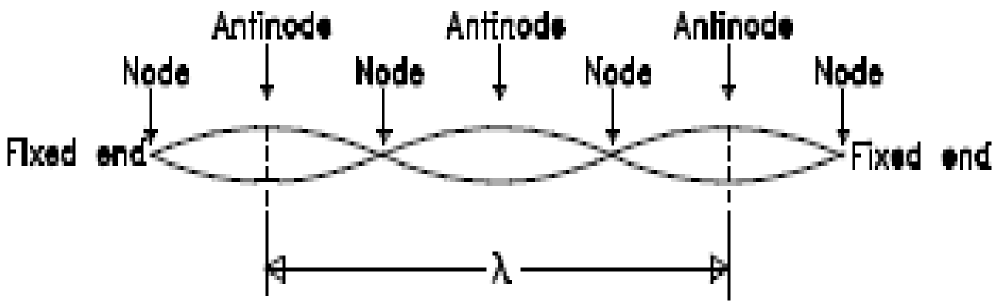
At some other points on the string, the two waves will move up and down together so that the amplitude of the disturbance at these points will be twice what it would be if only wave were present. This condition is known as constructive interference and the points at which this occurs are called antinodes.

As long as the λ ,f, and A of the waves remain fixed, the positions of the nodes and antinodes will not change. The pattern produced in this circumstance is called a standing wave. The analytic description for the displacement versus position and time with one end fixed at $x = 0$ is given by

$$A.\sin\left[\frac{2\pi}{\lambda}\,\mathrm{x}\right]\cos[2\pi.f.t]$$

Remember that a standing wave is produced by the interference of two waves travelling in opposite directions.

A string with both ends fixed can be excited with standing waves as shown in the figure below. The fixed ends of the string cannot move, so the string has nodes at these points. It is evident that the distance between the node at a fixed end and the first antinode is$\lambda/4$;



The distance between successive nodes (or antinodes) is $\lambda/2$. (See figure above.) The positions on the string where $A.\sin[2\pi/\lambda\ .\ \mathrm{x}] = 0$ correspond to a node, so whenever $[2\pi/\lambda\ .\ \mathrm{x}]$ is a multiple of π, i.e.

$$\left[\frac{2\delta}{e}\,\mathrm{x}\right] = \ \mathrm{n}.\delta$$

(x is a multiple of $\lambda/2$) we find a node. Midway between two nodes we will always find an antinode, a point where the string oscillates maximally.

Sound waves can be created in a tube of gas as standing waves. In this part of the experiment, a tuning fork vibrates at a frequency f over the open end of a tube containing air. The tube is closed, or sealed, at the other end by the water. The motion of the fork causes longitudinal sound waves to travel down the tube. The sound wave is reflected back up from the closed end of the tube so that the incident and reflected waves interfere with each other. The air at the closed end of the tube is not free to move, so if a standing wave is to be produced in the tube, a node must exist at the closed end. The air in the open end of the tube is free to move; so when a standing wave is produced in the tube, the open end will be an antinode.

Since the distance between a node and the nearest antinode in a standing wave pattern is $\lambda/4$, it should be evident that the shortest tube in which a standing wave can be established has a length of $\lambda/4$. A standing wave with wavelength λ can be established in longer tubes. All that is required is that a node exist at the closed end and an antinode at the open end i.e., that the length of the air column is an odd multiple of $\lambda/4$. When a standing wave is produced in the tube, a resonance condition is established and the intensity of the sound will increase.

Pre-lab questions

1. Is a wave on the water surface a longitudinal or transverse wave?
2. The wavelength of visible light is between 400-800nm. What is the frequency of visible light?

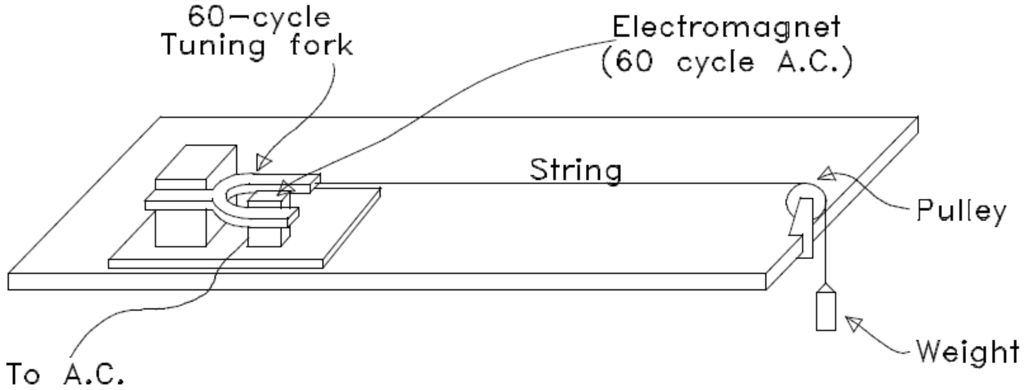
Materials & Equipment

60-cycle Tuning fork
Electromagnet (60-cycle A.C.)
String
Hanging weight, 100 g
Pulley with clamps
Lab Balance
Air column, open both ends
Rubber tubing
Meter stick
Water reservoir

Procedure

A- Standing waves on a String

The first part of the experiment deals with transverse waves on a string. A long horizontal string is attached to the tine of a driven tuning fork that vibrates at f = 60 Hz. The other end is fixed at a point where it passes over a pulley. You can change the distance between the pulley and the tuning fork by shifting the base of the tuning fork and you can hang weights M on the end of the string (which produces a string tension ($\mathbf{T} = M \times g$). The apparatus is pictured in the figure below.

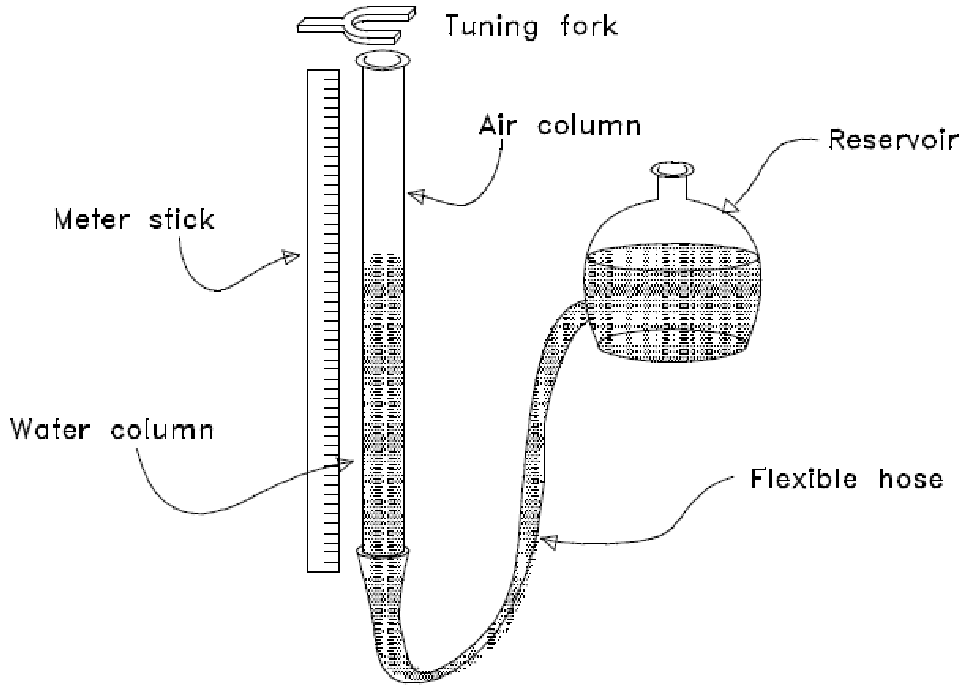


Step by Step List

1. Measure the mass and length of the string. Calculate μ.
2. Attach the string to the screw on the tuning fork and place it over the pulley.
3. Put a mass of 100g on the end of the string and choose the distance between pulley and tuning fork such that you get a standing pattern of nodes and antinodes.
4. Measure the distance between adjacent nodes (including uncertainty!) and calculate the wavelength. You get the best results if you measure nodes in the middle of the string and if you average over several measurements.
5. Calculate the experimental and the theoretical value of c and compare them. Are they equal within uncertainty?
6. Do these measurements for 3 different weights!

B- Standing Sound Waves

In the second part, we measure the wavelength of standing longitudinal waves. Sound waves (longitudinal waves) are set up in a long open tube, which is partly filled with water, as shown in the figure below.



We change the height of the water column by lifting or lowering a water reservoir. Produce a sound wave using a tuning fork (you will have two different ones, one with 512 Hz and one with 1024 Hz). Strike the tuning fork and hold it at the top of the glass tube. As you change the level of water in the tube, you find some water levels at which the sound from the tuning fork becomes much louder. This occurs whenever you have created a standing sound wave in the glass tube.

By measuring the distances between water levels that achieve successive sound maxima, you can determine the wavelengths of the sound waves. As before, from the wavelengths of the standing waves and the frequencies, you can compute the velocity of propagation of the sound waves for each case. This should equal the speed of sound in air.

Step by Step List

1. Measure the wavelength for both tuning forks. There should be small string-rings on the glass tube that you can use to mark the levels at which you get resonance (standing waves). To improve your data try to average over several measured values. Also don't forget to include uncertainties.
2. Calculate the speed of sound for both frequencies. Do you get the same value within uncertainty?
3. Is your value for the speed of sound close to the standard value of 340 m/s? What could be reasons that you get a different value?
4. Was one of the tuning forks easier to hear than the other? If yes, do you have an idea why?
5. Give the main sources of error and make suggestions of how the setup could be improved!

Calculations

Your task is to measure the resulting wavelengths of standing waves for various values of the tension. How is this done? In the theory, it was stated that the distance between two nodes in a standing wave is $\lambda/2$. So simply measure the distance between adjacent nodes and double it to get the wavelength.

Also calculate the velocity with which the wave propagates on the string, using the relation between frequency and wavelength. One can also analytically calculate the velocity of propagation of waves on a string from the physical properties of the string:

$$c = \sqrt{\frac{\mathbf{T}}{\mu}}$$

where $\mathbf{T}$ is the tension, and μ is the mass per unit length of the string. You can compare your experimental results with this prediction

Post-lab Questions:

1. A transformer is humming at a frequency of 60 Hz and produces a standing wave.
2. What is the distance between adjacent nodes? What is the distance between adjacent antinodes?

3. You have a string and produce waves on it with 50 Hz. The wavelength you measure is
4. 7 cm. What is the speed of the wave on this string?
5. You put a mass of 400g on the string of experiment 1. (The string is 50 cm long and weight 12.5g) What distance between adjacent nodes do you then expect for a frequency of 100Hz. (Use $g = 10\ m/s^2$)
6. With a 660 Hz tuning fork you measure a distance of 25□2 cm between adjacent nodes.
7. Is the value of c = 340 m/s within the uncertainty of your measured value?

Experiment 11: Heat and Temperature (First Law of Thermodynamics)

Objectives

1. Examine conservation of energy concept and first law of thermodynamics.
2. To measure the **specific heat capacity** of unknown metal samples.

Theory

Temperature is the most direct way in which we can sense and measure the presence of thermal energy. However, the relationship between temperature and heat is not as straightforward as we might think. In particular, each substance has its own *heat capacity*, which is a way of characterizing the amount of heat that a certain substance (say, water) requires in order to experience a 1- degree rise in temperature. Substances which have a high heat capacity, such as water, require a lot of heat energy to experience a significant change in temperature, while others, such as most metals, have a low heat capacity, and require very little heat energy to experience a large change in temperature.

The relationship between heat and temperature of any closed system is expressed by the First Law of Thermodynamics. The discovery of the First Law of Thermodynamics was made by Rudolf Clausius in 1850. Clausius stated that "*The change in the internal energy of a closed system is equal to the amount of heat supplied to the system, minus the amount of work performed by the system on its surroundings*". The law can also be stated: The energy of an isolated system is constant.

In mathematical terms, if an object does not change phase, then the change in its thermal energy (or internal energy), ΔE, depends directly on the change in its temperature, ΔT:

$$\Delta \boldsymbol{E} = \boldsymbol{mc}\Delta \boldsymbol{T} \ldots\ldots$$ --

Eq. 11.1

where *m* is mass and *c* is *specific heat capacity* or heat capacity per mass of material.

According to conservation of energy, when heat is introduced to a certain amount of isolated water, then the change of internal energy of water is equal to the heat introduced to it. Then Eq 11.1 can be written as follows:

$$Q = mc\Delta T \text{ -- } \textbf{Eq. 11.2}$$

Where Q is the heat introduced to the water.

On the other hand, when two bodies having different temperatures come into contact with each other, heat energy is transferred between the bodies. Take, for example, placing a piece of hot metal into a container of cool water. From experience we know over time that the metal sample will become cooler, while the water **and its container** will become warmer, until an **equilibrium temperature** is reached. In other words, according to the **law of energy conservation** the total heat energy **lost** by the metal is the total heat energy **gained** by the water and container:

$$-Q_{hot} = Q_{cold} \text{ -- } \textbf{Eq. 11.3}$$

$$-Q_m = Q_w + Q_c \text{ --- } \textbf{Eq. 11.4}$$

$$-m_m C_m \Delta T_m = m_w C_w \Delta T_w + m_c c_c \Delta T_c \text{ ------------------------ } \textbf{Eq. 11.5}$$

The hot side is set to be negative because energy is leaving the hot sample. Equation 11.5 holds true if no heat is exchanged with the surrounding environment **and** if none of the materials undergo a **phase change**.

To isolate this experiment from the environment we will utilize two types of **calorimeters**: a simple styrofoam cup and a more traditional wooden calorimeter with an aluminum cup insert. You will use Equation 11.5 to determine the *specific heat capacity* of a metal used in this experiment. Note that equations 11.2 and 11.3 assume that thermal energy is not lost to the environment.

The units of c depend on the units we are using to measure heat, temperature and mass. In fact, several measures of heat are defined by the heat capacity of water. ***The calorie is the amount of heat required to raise the temperature of one gram of water by one degree Celsius in temperature***. The *BTU* or ***British Thermal Unit***

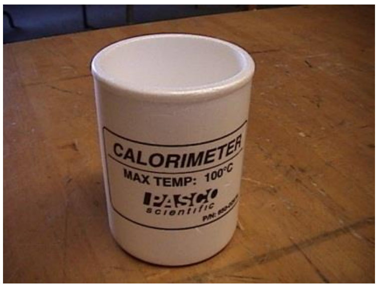
is the amount of heat needed to raise the temperature of one pound of water by one degree Fahrenheit. Each unit is a measure of heat energy, but obviously, it takes many calories of heat to equal one BTU. In addition, each unit has a fixed relationship to the measure of work energy, joules.

Energy Unit	In joules	In calories	In BTU
1 joule	1	0.239	9.49 x 104
1 calorie	4.18	1	3.97×10^{-3}
1 BTU	1055	252	1

Pre-lab Questions

1. What are the SI units for work, heat and specific heat capacity?
2. Which temperature scale should be used in the law of conservation of energy?
3. An amount of 4250 joule of heat was applied to a block of 750 g Iron (c= 25.10 $J.mol^{-1}.K^{-1}$) at T= 25 C. what is the final temperature of the iron block? Consider units conversion carefully.

Materials & Equipment



Styrofoam cup (or wooden),f 300 mL size

Steel cup, 300 mL size

Heating coil

Cold water

Thermometer

Laboratory balance

Metal Object

Lab timer or stopwatch

Procedure

Part I: Measuring the amount of heat produced by a heat source

In this part of the experiment, we will determine the amount of heat introduced to a certain amount of water during heating process. The source of heating can be a little heating coil used in heating up water in cups for making tea or instant coffee. To find out how much heat that is, we will use the known heat capacity of room temperature water (at 15 ℃), which is $C_{water} = 1 \frac{cal}{g.℃}$

1. Put 100 mL water in a Styrofoam cup. Each mL of water has a 1 g of mass.
2. Measure the temperature of the water as T_1.
3. Fix the heating coil and the thermometer with a stand clamp to be immersed in the water.
4. Start heating the water with time. Record the time and temperature every 1 minute intervals.
5. When heating water in your cup, remember that the water should be stirred continuously to make sure that all of the water is at the same temperature. One partner should be stirring the water, while the others record time and temperature.
6. Continue heating for 10 minutes then lift the heating coil from the cup. The last temperature measurement will be T_2.
7. Repeat steps 1-4 for three trials using fresh tab water each time, and record your measurements in the Data Table.

Calculations

1. Calculate the temperature change ΔT *as* the difference between the highest temperature and the temperature you started at.
2. Calculate the total amount of heat introduced to the water by using Eq. 11.2.

Part II: Determination the specific heat capacity of a metal

1. Prior to the experiment, obtain two samples of the **same** metal and place them both in a hot water bath. Allow enough time for the samples to reach an equilibrium temperature. Measure the temperature of the metal immediately when using it in the experiment.
2. Fill 2/3 of the Styrofoam cup with cold water. Measure the cold water temperature.

3. Put the metal sample in the Styrofoam cup. When using the styrofoam cup you may assume that there is no heat lost or gained by the styrofoam cup. That is, we can assume $C_c = \infty$ while $\Delta T_c = 0$ and therefore no heat is transferred to the cup. Is there a way to determine if this is a valid assumption?
4. Repeat steps 1-3 for three trials for each type of metal and record your measurements in the Data Table.

Calculations

1. Use Equation 11.5 to determine the specific heat C_m of the metal sample and ascertain the identity of the metal sample.
2. Calculate the percentage error of heat capacity C_m by comparing the calculated value with the listed value in literature.

Post-lab Questions:

1. In your discussion, explain why the heat loss to the surroundings produces a systematic error that makes your measured final temperatures *smaller* than they would be without the heat loss. Also explain why that would make your calculated specific heat systematically too large.
2. Identify other sources of systematic error in the experiment, and state whether each source would make your calculated specific heat too small or too large. Suggest a procedure to measure, minimize, or eliminate each source of systematic error.
3. Discuss the difference between the theoretical and experimental values of specific heat capacity of metals.

Experiment 12: Thermal Linear Expansion of Metals

Objectives

1. To measure the thermal coefficient of linear expansion of several metal rods.
2. To incorporate simple mathematical modeling techniques to fit curves to empirical data.

Theory

With few exceptions solids increase in size as the temperature is raised. It is obvious that the change in length ΔL of a solid depends upon its length L and upon the change in temperature surrounding the rod, ΔT. It is found experimentally that ΔL is proportional to L and ΔT, or

$$\Delta \boldsymbol{L} = \boldsymbol{\alpha L \Delta T} \quad \text{---} \quad \textbf{Eq. 12.1}$$

where the constant of proportionality alpha is called the coefficient of linear expansion. Since L and ΔL are measured in the same units, then ΔL/L is the fractional change in length and α is the fractional change in length per degree change in temperature. Since the fractional change in length is a pure number, the unit in expressing the magnitude of is simply "per degree Centigrade".

The values of a given in the tables is always based upon the length L_0 of the body at 0 ℃ and the above equation should read

$$\Delta \boldsymbol{L} = \boldsymbol{\alpha L_0 \Delta T} \quad \text{--} \quad \textbf{Eq. 12.2}$$

From Equation 12.2, we see that $\boldsymbol{\Delta L}$, is not only dependent on $\boldsymbol{\Delta T}$, but also on the initial length of the object, $\boldsymbol{L_0}$. So, the longer the object, the greater change in its length. Although the phenomena of linear thermal expansion can be problematic when designing bridges, buildings, aircraft and spacecraft, it can be put to beneficial uses. For instance, household thermostats and bi-metallic strips make use of the property of linear expansion. From Equation 12.2 it follows that the length L of a body at the temperature T ℃ is given by the relation

Table 12.1: Linear Expansion Coefficient Values of Common Materials	
Material	□ **($x10^{-5}$ °C^{-1})**
Glass (ordinary)	0.09
Glass (Pyrex)	0.32

$$L = L_0(1 + \alpha\Delta T) \quad \text{Eq. 12.3}$$

Table (1) shows a list of linear expansion coefficient values for some materials.

Concrete	1.20
Steel	1.24
Copper	1.76
Aluminum	2.34
Lead	2.90

http://prb.aps.org/abstract/PRB/v56/i13/p7767_1

The apparatus to be used in this experiment is shown in figure 12.1. It consists of a steam jacket containing a metal rod about 0.6 m long. The jacket is held by two supports by either end. One of the end supports has a thumbscrew to keep this end of the rod fixed. The other end contains an indicator to measure the change in length of the rod.

There are two types of indicators. One has a micrometer screw with a rotary dial of 100 divisions. Each division is 0.01 mm, one complete turn of the dial is equivalent to a linear translation of 1 mm. the second type of indicator contains a plunger-activated dial that reads directly in 0.01-mm increments. One complete revolution of the dial corresponds to 1 mm of linear displacement.

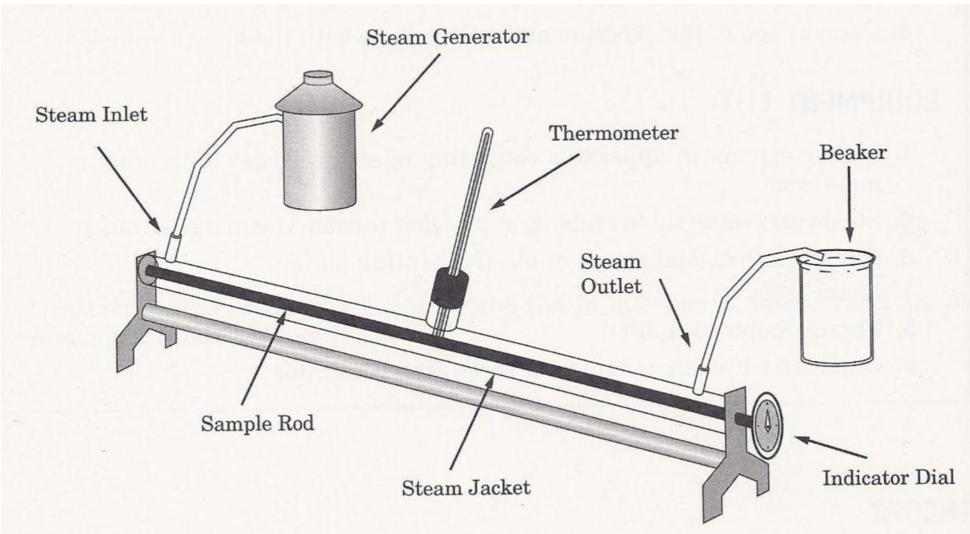


Fig. 12.1 Linear Expansion Apparatus for Metals.

Pre-lab Questions

1. In this experiment, you should have at least 3 data points using cold water, hot water, and steam. In what order will you proceed? Why?
2. What are your initial conditions? What, if anything, will you measure before heating or cooling the metal rods?
3. What parameters will you graph in order to measure the linear expansion coefficient, α,
4. Glass Beakers should be made of material having a low coefficient of expansion. Explain why.

Materials & Equipment

Three metal rods (Al, Cu, and steel)

Linear expansion apparatus consisting of steam jacket

Steam generator with barometer,

Beaker to collect condensed steam, Rubber tubing

Bunzen burner and stand

Clamps, Paper towels

Meter stick

Micrometer

Thermometer

Procedure

1. Remove the rod from the steam jacket and measure its length to the nearest 0.001 m. record this as L_0 in your Data Table.
2. Replace the rod in the steam jacket, arrange the apparatus as shown in Figure 12.1 and make sure that the rod rests firmly against the indicator.
3. Using a one-holed rubber stopper, place a thermometer in the opening for that purpose. The thermometer bulb should barely touch the rod. The water flows from the faucet, through the jacket J and out the outlet O into the sink. When the temperature of the tap water has become constant, as indicated by the thermometer T, read the temperature. When the temperature of the

tap water has become constant, as indicated by the thermometer T, read the temperature and record as T_0 in the Data Table.

4. Adjust the indicator dial until contact is made with the rod. Record the indicator dial position as D_0.
5. Slowly rotate the micrometer screw indicator until the point of the screw makes contact with R, and take five independent readings of the micrometer. Care should be taken not to force the indicator too hard against the rod.
6. Turn off the water, disconnect the rubber tubing and join it to the steam generator.
7. After letting the steam escape from the outlet O for one or two minutes, take five readings of the micrometer and also read the thermometer for each time of your readings.
8. Read the barometer and, using steam tables, determine the temperature of the steam under existing atmospheric pressure, which is, of course, also the temperature of the rod. Although the thermometer T should be read for comparison purposes, it reads too low, owing to the fact that the thermometer is calibrated for complete immersion but that in this particular case the mercury in the exposed stem is not at the temperature of the steam. The correct temperature is determined from steam tables, not from the thermometer reading.
9. Measure the length of the rod with a meter stick and use Equation 12.2 to compute the coefficient of linear expansion of the material. Compare this value with the accepted value for a.
10. Repeat this for the remaining rods given.

Hints and Cautions

1. **Caution!!!** Rods may be very hot when using the steam generator! Use the hand protectors to remove hot rods.

2. Get your TA to check your steam generator between uses. If the water level is not at the proper level, you will experience time consuming problems.
3. Think before you start! You will be using a large amount of water throughout this lab; make sure your setup allows the water to flow smoothly and that you have a continuous supply of water available!
4. You will be given a limited amount of ice. Your experiment should be designed so that the ice lasts for the duration of that day's experiment.

Calculations

1. Calculate the increase in length ΔL for each rod. $\Delta L = D_1 - D_0$ and record each of them in the Calculation Table.
2. Calculate the increase in temperature ΔT for each rod from $\Delta T = T_1 - T_0$ and record each of them in the Calculation Table.
3. Using equation 12.2 calculate the linear coefficient of thermal expansion α for each rod and record each of them in the Calculation Table.
4. Calculate the percentage error for each experimental value of α compared to the known value. Record them in the Calculation Table.

Post-lab Questions:

1. How did your value of a, compare to the accepted values listed in Table 1?
2. How did the linear expansion coefficients for copper, aluminum and steel compare? How can you interpret this?
3. What percentage error was introduced in this experiment by substituting the length of the rod at room temperature for the 0 ℃ length? Did this introduce a significant error into the experiment?
4. A hole is drilled in a metal plate. When the temperature of the plate is raised does the hole get smaller or larger? Why?
5. From your results, can you approximate the coefficient of volume expansion for aluminum, copper, and steel? That is, $\Delta V = \beta V_i \Delta T$. Give your answer in terms of α.

References

1. D. H. Loyd. (1998). PHYSICS Laboratory Manual. *Harcourt College Publishers.* 2nd Ed.
2. Experiments in Physics. General Physics I Lab. Columbia University, Department of Physics. Fall 2011.
3. M. Hynes. Lab Manual, Physics 117/197, Washington University in St. Louis. Fall 2011.
4. P. Wang. Physics for Society. Lab Manual, Department of Physics, Western Illinois University. Fall 2011.
5. Physics 111: College Physics Laboratory, Laboratory Manual. Montana State University-Billings.
6. B. Cudnik, M. Rahman, and Sh. Williams. Physics 2111. Laboratory Manual. Florida State University. Spring 2011.
7. PHY111: General Physics I, Laboratory Manual. Student's Edition. Spelman College. Fall 2007.