General Physics Laboratory Handbook

A Description of Computer-Aided Experiments in General Physics

Group I

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Introduction

Physics is an experimental science. Laboratories offer an ideal opportunity to learn and strengthen, by means of actual observations, some of the principles and laws of physics that are taught to you in general physics lectures. You will also become familiar with modern measuring equipment and computers, and learn the fundamentals of preparing a report of the results.

1. General Instructions

1. You are expected to arrive on time since instructions are given and announcements are made at the start of class.

2. A work station and lab partners will be assigned to you in the first lab meeting. You will do experiments in a group but you are expected to bear your share of responsibility in doing the experiments. You must actively participate in obtaining the data and not merely watch your partners do it for you.

3. The assigned work station must be kept neat and clean at all times. Coats/jackets must be hung at the appropriate place, and all personal possessions other than those needed for the lab should be kept in the table drawers or under the table.

4. The data must be recorded neatly with a sharp pencil and presented in a logical way. You may want to record the data values, with units, in columns and identify the quantity that is being measured at the top of each column.

5. If a mistake is made in recording a datum item, cancel the wrong value by drawing a fine line through it and record the correct value legibly.

6. Get your data sheet signed by the instructor before you leave the laboratory. This will be the only valid proof that you actually did the experiment.

7. Each student, even though working in a group, will have his or her own data sheet and submit his or her own typed report, for grading to the instructor at the next scheduled lab session. No late reports will be accepted.

8. Actual data must be used in preparing the report. Use of fabricated, altered, and other students’ data in your report will be considered as cheating. No credit will be given for that particular lab and the matter will be reported to the Dean of Students.

9. Be honest and report your results truthfully. If there is an unreasonable discrepancy from the expected results, give the best possible explanation.

10. If you must be absent, let your instructor know as soon as possible. A missed lab can be made up only if a written valid excuse is brought to the attention of your instructor within a week of the missed lab.

11. You should bring your calculator, a straight-edge scale and other accessories to class; it might be advantageous to do some quick calculations on your data to make sure that there are no gross errors.

12. Eating, drinking, and smoking in the laboratory are not permitted.

13. Refrain from making undue noise and disturbance.
2. Report Format

The laboratory report must include the following:

1. **Title Page**: This page should only carry the student’s name, ID number, the name of the experiment, and the names of the student’s partners (listed under ‘partners’).

2. **Objective of the Experiment**: This is a statement giving the purpose of the experiment.

3. **Theory**: You should summarize the equations used in the calculations to arrive at the results for each part of the experiment.

4. **Apparatus**: List the equipment used to do the experiment.

5. **Procedure**: Describe in your own words how the experiment was carried out.

6. **Calculations and Results**: Provide one sample calculation to show the use of the equations. Present your results in tabular form that is understandable and can be easily followed by the grader. Use graphs and diagrams, whenever they are required. Include the comparison of the computed results with the accepted values together with the pertinent percentage errors. Give a brief discussion for the sources of the errors.

7. **Conclusions**: Relate the results of your experiment to the stated objective.

8. **Data Sheet**: Attach the data sheet for the experiment that has been signed by your instructor.
Measurements

Theory
No physical measurement is ever exact, but one must be precise about the extent of inexactness. In communicating results, one must in general indicate to what degree the experimenter has confidence in the measurement. Usually this is done by the number of significant digits. For example, the lengths of 2.76 cm and 3.54 \times 10^3 \text{ cm} both have three significant digits. As a common practice the significant digits will include those numbers taken directly from the scale and one estimated place. When adding (subtracting) numbers, find the position of the first (counted from the left) estimated figure and round all numbers to this position. For example, the sum 6.85+9.376+8.3782 would be 24.61, since the 6.85 has the estimated figure (5) in the hundredth’s position, and we round the next two numbers to 9.38 and 8.38, respectively. For multiplication and division, the result should be rounded to as many significant digits as the least accurate of the factors. For example, when calculating the product of 18.76 and 9.57 the less accurate factor has 3 significant digits so the product, 180, will also have 3 significant digits.

Regardless of how carefully a measurement is made, there is always some uncertainty in the measurement; this uncertainty is called error. Errors are not necessarily mistakes, blunders or accidents. There are two classes of errors, systematic and random. They occur because of problems with the reading of the instrument or because of some external factor such as temperature, humidity, etc. These errors can be corrected if they are known to be present. Calibration techniques, attention to conditions surrounding the measurements, and changing operators are used to reduce system error. The random errors are by nature, erratic. They are subject to the laws of probability or chance. It is to such errors that experimental statistics is applied.

The effect of random errors may be lessened by taking a large number of measurements. For a large number of measurement the most probable value of the quantity, the average or mean, is obtained by adding all the readings and dividing by the number of readings. The average deviation (a.d.) is obtained by adding the absolute value of the difference between each reading and the mean and dividing by the number of readings. The average deviation of the mean (A.D.), sometimes referred to as the “experimental error”, is the average deviation divided by the square root of the number of observations. The standard deviation is also a measure of the uncertainty of a measurement. Values are quoted for measurements as a “value ± error”, where “error” is usually the A.D., the average deviation of the mean, e.g., \( x \pm A.D. \), or the standard deviation, e.g., \( x \pm \sigma \).

The usual experimental procedure is to make a large number of measurements. For this course you will normally make several measurement of each quantity and calculate an average and A.D. or \( \sigma \). Frequently, you will compare your measurements to known values or to a value calculated from a straightforward derivation. Results of this comparison can be expressed in terms of either the absolute or the relative error. As the latter is often presented as a percentage (or, with much higher precision, in ‘parts-per-million’), relative error is also often called the percentage error. The relative error is the absolute value of the difference between the “standard value” and the “experimental value” divided by the “standard value.” The percentage error is the relative error multiplied by 100%.
Table 1. Some useful formulae.

<table>
<thead>
<tr>
<th>Average or Mean</th>
<th>$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Deviation</td>
<td>$a.d. = \frac{1}{N} \sum_{i=1}^{N}</td>
</tr>
<tr>
<td>Average Deviation of the Mean</td>
<td>$A.D. = \frac{a.d.}{\sqrt{N}}$</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}}$</td>
</tr>
<tr>
<td>Percentage Error from standard (accepted) value $x_s$</td>
<td>$% \text{ error} = \left</td>
</tr>
<tr>
<td>Volume of a Rectangular Block</td>
<td>$V = L \times W \times H$</td>
</tr>
<tr>
<td>Volume of a Sphere</td>
<td>$V = \frac{4}{3} \pi r^3$</td>
</tr>
<tr>
<td>Density of an Object of Mass $m$ and Volume $V$</td>
<td>$\rho = \frac{m}{V}$</td>
</tr>
</tbody>
</table>

Volumes are based on cube units of length. The volume of an object gives the number of cubic length units that it contains. Volumes are most often expressed in cubic centimeters (cc or cm$^3$), cubic meters (m$^3$), or liters (L). Mass is a measure of the amount of material that an object contains. Mass is usually expressed in grams (g) or kilograms (kg). Density is a property of matter defined as mass per unit volume. Density is most commonly expressed as g/cm$^3$ or kg/m$^3$.

**Exercise 1**

Perform the indicated operation giving the answer to the correct amount of significant digits.

A. $15.3 \times 7.9 = \underline{\hspace{1cm}}$

D. $15.3 \div 7.9 = \underline{\hspace{1cm}}$

B. $16.47 - 4.2 = \underline{\hspace{1cm}}$

E. $1.2 \times 10^{-3} - 0.001 = \underline{\hspace{1cm}}$

C. $3.14 + 360 = \underline{\hspace{1cm}}$

**Exercise 2**

Determine if the following errors are random or systematic.

1. When measuring a sample six times, the balance gives four different values for the mass.
   Error: ________________

2. The electronic balance gives a reading that is 0.12 g too low for all mass measurements.
3. A caliper gives different values for length of a block when measured by four different individuals.

Error:___________________

4. A thermometer reads temperatures that are too 0.2 °C too high for every measurement.

Error:___________________

**Exercise 3**

Using a vernier caliper, the following values were measured for a block:

12.32 cm, 12.35 cm, 12.34 cm, 12.38 cm, 12.32 cm, 12.36 cm, and 12.38 cm.

Calculate the mean, the average deviation, the average deviation of the mean, and the standard deviation.

Mean:__________ a.d.:__________ A.D.:__________ σ:__________
Experiment

**Objective:** The student will measure the fundamental quantities of length and mass. Secondary quantities of volume and density will be determined for the measured quantities. Each group will measure these quantities using the measuring instruments and data will be shared amongst the group members.

**Apparatus:** Electronic caliper, meter stick, balance.

**Dimensions of Block (Determining Volume):** Each group will be provided with a block. Using the electronic caliper two group members will measure the length, width, and height of the block. Using the meter stick, two group members will measure the length, width and height of the block. All group members will record each group member’s values for the dimensions of the block in table 2 along with the name of the group member conducting the measurement. Next, calculate the volume of the block using the formula provided in table 1. Using your group’s data determine the best value for the volume of the block (average or mean) and the standard deviation in this value.

**Mass of Sphere (Determining Density):** Using the caliper, allow two group members to measure the diameter of the metal sphere and record these values in table 3. Next, have two group members measure the diameter of the sphere also using the caliper. Have two group members use one balance to obtain the mass of the sphere, and two group members use another balance to obtain the mass of the sphere. Calculate the volume of the sphere. Using your measured value for the mass and the calculated value for the volume, determine the density of the sphere. Using your data and data provided by group members, determine the best value for the density of the block (mean) and the average deviation of the mean. Using the “standard value” for density provided by the instructor, determine the percentage error in your measurement.
## Data Sheet

<table>
<thead>
<tr>
<th>Group Member</th>
<th>Length (L)</th>
<th>Width (W)</th>
<th>Height (H)</th>
<th>Volume (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Average Volume:**

**Standard Deviation in Volume:**

Best Value for Volume of Block = _______________ ± _______________ in units of _______________.

Table 2: Measurements for calculating the volume of a block.

<table>
<thead>
<tr>
<th>Group Member</th>
<th>Mass</th>
<th>Diameter</th>
<th>Radius</th>
<th>Volume</th>
<th>Density (ρ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Average Density:**

**Average Deviation in Density:**

Best Value for Density of Sphere = _______________ ± _______________ in units of _______________.

% Error: _______________

Table 3: Measurements for calculating the density of a sphere.

Lab Instructor: ____________________________
Vector Force Table

Objective: The objective of this experiment is to study vectors and compare experimental results with graphical and analytical calculations by finding a resultant force that balances out the given force so that the system will be in equilibrium.

Apparatus: Force table, weight holders, sets of masses, rulers, protractors, spirit levels.

Theory: Vectors $A$ and $B$ can be added graphically by drawing them to scale and aligning them head to tail. The vector that connects the tail of $A$ to the head of $B$ is the resultant vector $R$. Vector addition is both associative and commutative.

The components ($A_x$ and $A_y$) of a vector $A$ can be calculated by projecting the length of $A$ onto the coordinate axes as shown in figure 1. The components can be obtained by using the following equations:

$$A_x = |A| \cos \theta_A, \quad A_y = |A| \sin \theta_A$$

![Figure 1](image.png)

The sign of a component gives its direction along the $x$ or $y$ axis. Conversely, from the components, the magnitude $|A|$ and direction $\theta$ of the vector can be calculated using the following:

$$|A| = \sqrt{A_x^2 + A_y^2}, \quad \theta = \tan^{-1}(A_y/A_x)$$

In order to add vectors analytically, they must be in component form. The components of a vector sum of two vectors $A$ and $B$ yields the components of a new vector, called a resultant vector and will be denoted by $R$. The components of $R$ can be calculated by:

$$R_x = A_x + B_x, \quad R_y = A_y + B_y$$

In this experiment, each group will find the direction and magnitude of a force $C$ that balances out the forces of $A$ and $B$ so that the system will be in equilibrium. In order to for the system to be in equilibrium, the following must hold:

$$A + B = -C, \quad A + B + C = 0$$
Procedure: Place the force table on a flat surface. Using the spirit level, make sure the force table is level. Cut three pieces of string ~21 inches long. Tie a loop at the end of each piece of string, and attach the other end of the string to the ring. Place the ring in the center of the force table so that it encircles the pin. Put the strings over the pulleys attached to the force table. Make sure that the pulleys are fixed at the same height around the table.

Get three mass holders. For vector A, add mass to one mass holder until the entire setup (mass holder and added mass) is ~27 g. Place this mass on the end of one of the strings looped over a pulley and set the pulley at an angle of 63°. For vector B, to the second mass holder, add mass until the entire setup is ~41 g. Place this mass on the end of one of the available strings looped over a pulley and set the pulley at an angle of 154°.

For vector C (the resultant), attach the last mass holder to the last string looped over a pulley. Add mass to the system and adjust the angle until the system is in equilibrium. When the system is in equilibrium, the ring with the attached strings will be parallel to and suspended above the ring painted on the force table, and the pin can be removed. Once equilibrium is reached, determine the entire mass for the setup of vector C.

Record the values for mass and angle for vectors A, B, and C in Table 1. Record the values for mass and angle of vectors A and B in Table 2. Use the formulas given to calculate the mass and x and y- components of vectors A and B, and calculate the mass, force, components, and angle for vector C.

Draw the vectors A, B, and C and their corresponding components to scale in the space provided. Also, draw the complete system of vectors A, B, and C together in the space provided. Be sure to label the vectors, forces and angles.

Compare the experimental results for mass and angle measure of vector C with the analytical calculations. Determine the percentage error.
### Experimental Results

Table 1. Experimental Results

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (g)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Θ (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Analytical Calculations

Table 2. Analytical Calculations

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (g)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force (N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x-component (N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y-component (N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Θ (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Graphical Sketches

Vector A

Vector B

Vector C

Vectors A, B, and C

Graphical Sketches.
Rectilinear Motion

**Purpose:** Students will analyze the relationship between the angle of an incline and the normal force and with the parallel forces of an object on the incline. The student will also calculate \( \mu \) and determine \( g \) while using acceleration at different inclines.

**Equipment:** 1.2m Pascar Dynamic track with PasCar, Computer interface (Science Workshop), Motion sensor, (2) 500 mg weights, caliper, and level.

\[
d = \frac{1}{2} at^2 + v_0 t + d_0, \text{ for a car on the incline plane.}
\]

Figure 1

Fit to:
\[
y = \alpha x^2 + \beta x + x_0
\]
\[
\alpha = \frac{1}{2} a
\]
\[
m \ddot{a} = \vec{F}_r = \vec{F}_D - \vec{F}_F \quad \text{from Figure 2.}
\]
\[
F_D = mg \sin \theta
\]
\[
F_F = \mu F_N
\]
\[
F_N = mg \cos \theta \approx mg \quad (\text{for small } \theta)
\]
$ma = mg \sin \theta - \mu mg \quad \left[ \sin \theta = \frac{h}{L} \right]$


\[
a = g(\sin \theta - \mu)
\]


\[
a_1 = g(\sin \theta_1 - \mu_1) = g\left(\frac{h_1}{L} - \mu_1\right)
\]

\[
\mu_1 = \frac{h_1}{L} \frac{a_1}{g}
\]

\[\frac{a_2}{a_1} = \frac{\left(h_2 - \mu_2\right)}{\left(h_1 - \mu_1\right)} = R_{21}, \quad \frac{a_3}{a_1} = \frac{\left(h_3 - \mu_3\right)}{\left(h_1 - \mu_1\right)} = R_{31}, \quad \frac{a_3}{a_2} = \frac{\left(h_3 - \mu_3\right)}{\left(h_2 - \mu_2\right)} = R_{32}
\]

assuming $\mu_2 \approx \mu_1 \approx \mu$, let $\mu = \mu_{21}$ then,

\[
\mu_{21} = \frac{(R_{21} \frac{h_1}{L} - \frac{h_2}{L})}{(R_{21} - 1)}, \quad \mu_{31} = \frac{(R_{31} \frac{h_1}{L} - \frac{h_3}{L})}{(R_{31} - 1)}, \quad \mu_{32} = \frac{(R_{32} \frac{h_2}{L} - \frac{h_3}{L})}{(R_{32} - 1)}
\]

get $\bar{\mu}$ from $\frac{\mu_{21} + \mu_{31} + \mu_{32}}{3}$

**Procedure:**

1. Adjust the incline of the ramp.
2. Observe the position vs. time graph.

Find the acceleration:

3. Start by making sure the track is level, then raise the height of one end of the track at least 1.5 cm but no more than 1.8 cm. Take the calipers and measure the height at 10 cm (on the track) from the table and also at 110 cm (on the track) from the table. Take the difference and find $h$ ($1.5 \text{ cm} \leq h_{\text{min}} \leq 1.8 \text{ cm}$, and the difference between each of the $h$’s should be at least 1 cm, ie. If $h_1$ is 1.5 cm then $h_2$ must be at least 2.5 cm but less than 2.8 cm and similar for $h_3$ which should be 1 cm above $h_2$), place the PAScar about 10 cm from the Motion Sensor. Simultaneously press the Start Button in DataStudio and release the PAScar. After the car has hit the bottom of the ramp press the Stop button in DataStudio. Using the “Fit-quadratic” button at the top of the graph, record the coefficients of the Position-Time graph. Print at least one graph for your records. The first coefficient, $a$, in the $2^{nd}$ order equation is equal to $(\frac{1}{2})a$ the acceleration for this run as shown on
the first page. Fit at least three curves for each height. From the average of α, find a. \(a = 2 \alpha\). Increase the height by at least 1 cm but no more than 1.3 cm and find the acceleration \(a_2\). Repeat the 1st procedure above and find \(a_3\).

4. After you finish each run enter the data in the table below.

5. Calculate \(\mu_1\), \(\mu_2\), and \(\mu_3\) using \(g = 9.8 \text{ m/s}^2\), and values for \(h_1\), \(h_2\), \(h_3\), \(a_1\), \(a_2\), and \(a_3\).

6. From \(a_2\) and \(a_1\) find \(R_{21}\).

7. From \(R_{21}\) find \(\mu_{21}\).

8. From \(\mu_{21}\) calculate \(g\).

9. Repeat and calculate \(g\) from \(\mu_{31}\) and from \(\mu_{32}\) and the average of the three \(\mu\)'s.

10. Calculate the error in \(g\) from \(R_{21}\), \(R_{31}\), and \(R_{32}\), average \(g\).

11. Calculate the average \(\mu\) from \(\mu_1\), \(\mu_2\), and \(\mu_3\) (calculations including \(a_1\), \(a_2\), and \(a_3\)).

12. Calculate the average \(\mu\) from \(\mu_{21}\), \(\mu_{31}\), and \(\mu_{32}\) (calculations including \(R_{21}\), \(R_{31}\), and \(R_{32}\)).

13. Compare \(\mu\) values and \(g\) values.

Table:

| \(h_1\) | \(h_2\) | \(h_3\) | \(a_1\) | \(a_2\) | \(a_3\) |
Newton’s Second Law states that the acceleration \( a \) of an object is directly proportional to the net (or unbalanced) force \( F_{\text{net}} \) acting on the object and inversely proportional to the total mass \( m_T \).

\[
a = \frac{F_{\text{net}}}{m_T}
\]  

The Atwood Machine is a standard device for the investigation of this relationship. This Machine consists of two masses connected by a string looped over a sensor. (See Figure.) When applied specifically to the Atwood Machine, the acceleration of the descending mass is given by

\[
a = \left( \frac{\Delta m}{m_T} \right) g
\]

where \( \Delta m = m \)

\( = \) mass of the ascending weights,

\( m = \) mass of the descending weights, \( m \) and \( m \), and

\( g = \) acceleration of gravity.

The acceleration is determined experimentally by using the PASCO 700 Interface and the PASCO Rotary Motion Sensor. This method provides a direct readout of the acceleration of the system by using a photodiode to measure the angular rotational speed of the sensor.

**Objective:** The objective of this experiment is to study Newton’s Second Law of Motion utilizing the Atwood Machine and to show that the acceleration is proportional to the force causing the motion.

**Apparatus:** Rotary motion sensor, thin string, weight hanger and weights, computer, PASCO Model 700 Interface, printer

**Procedure:**

1. Verify that the rotary motion sensor is mounted securely and stable.
2. The PASCO Model 700 Interface Must be turned on prior to turning on the computer.
3. Make sure that the support rod is mounted so that the masses can move freely vertically without swinging.
4. Mount the rotary motion sensor and support rod on a table that have sufficient space for the masses to move up and down on either side of the rotary motion sensor. The axis of the sensor should be horizontal and higher than 1 meter.
above the floor.
5. Add weights until the load including the mass of the hanger on each side is 200 g.
6. Make sure the system machine doesn’t move.
7. In order to avoid negative values of the position x and the velocity v, choose the descending side to be the left side on which you are going to add extra masses.
8. Add an extra mass of 12 g on the left side and release the system.
9. From the graph that give the velocity vs. time, t, calculate the acceleration, a, of the motion using the slopes of the lines. Infer the value of the acceleration due to gravity, g, for each extra mass Δm.
10. Calculate the average of the gravity acceleration, g, and the experimental error.
Conservation of Momentum: The Ballistic Pendulum

Object: To study the elements of projectile motion and the law of conservation of momentum.

Theory: The Ballistic Pendulum provides the introductory Physics student with an opportunity to study several different physical principles in a single experiment. The ballistic pendulum provides an inelastic collision in a system that provides measurement of the initial and final velocities. In order to determine these velocities one must use projectile motion and the conservation of energy. The projectile is a ball that is force forward by a compressed spring. The spring tension should not be changed at anytime during the experiment. The ball is shot into the pendulum which should be still and vertical. The ball and pendulum swing together to the side and will be stuck on a curved, grooved track. The pendulum hole has a flexible metal spring which breaks easily. Push the metal strip gently into the hole and out of the way before allowing the ball to drop out. DO NOT PUSH THE BALL OUT !!!!!!!!!!!!!!!

There is a marker on the side of the pendulum. That marker represents the center of gravity of the ball and pendulum. The height change of that marker is proportional to the potential energy change of the unit. In this case, the kinetic energy that the ball and pendulum have when the ball collides with the pendulum is equal to the change in the potential energy of the two. You will use projectile motion and conservation of energy to show conservation of momentum in an inelastic collision.

Apparatus:
Blackwood Ballistic pendulum, meter stick, level, carbon paper, sheet of white paper, plumb bob.

Procedure:
1. The pendulum is raised up out of the way. The apparatus is set near the edge of the table and is leveled by adding wedges of paper to the base of the apparatus. Make sure that you have a clear area and there is no danger than the ball will be projected out of the window or hit any one. Fire the gun, note the location of impact. Do not change the position to the gun, do not change the spring compression. Tape a piece of carbon paper, face down on a sheet of white paper, with another sheet of paper on the carbon paper to protect it. You will not change the spring at all. Make at least three trials for the horizontal range. Expose the bottom sheet of paper. Measure the distance from a point just under where the ball leaves the gun as determined by the plumb bob to the spots on the paper. Average the values. Measure the vertical distance from the level of the guns to the floor. These two bits of data, the vertical height and the range with the equations for rectilinear motion enable you to determine the velocity of the gun.
2. Release the pendulum so that it falls freely. Fire the ball into the pendulum and record the position reached by the pendulum. Repeat the procedure six times. Record the number of grooves through which the pendulum rose. Average the readings, set the pendulum at the average position, measure the height of the pointer on the side of the pendulum. Record the lowest position of the pendulum, that is, when the pendulum is vertical. This difference in heights is the one used to calculate the change potential energy of the pendulum plus ball.

3. Remove the pendulum from its support and measure the mass of the pendulum and that of the ball.

4. Determine the initial speed of the ball.

5. Compute the momentum of the ball just before the collision and that of the ball and pendulum just after the collision. Compare the two quantities.

6. Compute the kinetic energy of the ball before the impact and the kinetic energy of the ball and pendulum after the collision.

7. Compare the quantities and explain any discrepancies.

\[ x = v_x t, \quad H = \frac{1}{2} gt^2 \]

\[ m_B v_x = (m_B + m_P) V \]

\[ V^2 = 2gh \]

<table>
<thead>
<tr>
<th>Reading</th>
<th>Angle ( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>39°</td>
</tr>
<tr>
<td>10</td>
<td>41.2°</td>
</tr>
<tr>
<td>20</td>
<td>43.5°</td>
</tr>
<tr>
<td>30</td>
<td>45.8°</td>
</tr>
<tr>
<td>40</td>
<td>48°</td>
</tr>
</tbody>
</table>

Ball mass \( \sim 69 \) gram  Pendulum \( \sim 268 \) gr.
**Simple Harmonic Motion**

1-Theory

Periodic motion or harmonic motion is motion that repeats itself at regular intervals of time. The simplest of all periodic motion is called simple harmonic motion (SHM). This motion is represented by a sinusoidal function of time. Mathematically it may be written as

\[ y(t) = y_m \cos(\omega t + \Phi), \]  

where \( y(t) \) is the displacement of the particle from its equilibrium position at time \( t \), \( y_m \) is the amplitude (maximal displacement), \( \omega \) is the angular frequency, and the constant \( \Phi \) is called the phase angle.

Imagine a spring (unstretched length \( l \)), that is hanging vertically from a support and is subjected to a stretching force, \( F \), by attaching a mass, \( m \), to its free end. Its length increases by \( \Delta l \). This force is balanced by the upward elastic force due to the spring called the restoring force. To a good approximation, for small elongations, the force exerted by the spring is proportional to the amount of stretch:

\[ F = -k \Delta l, \]

where \( k \) is called the spring constant. Eq. (2) expresses Hooke’s law. If the mass is now pulled down a small distance from the equilibrium position and then released, the restoring force causes the mass to oscillate up and down. Hooke’s law gives the restoring force to be

\[ F(t) = -ky(t) = -ky_m \cos(\omega t + \Phi) \]

where \( y(t) \) is the distance of the mass from its equilibrium position.

\[ F(t) = ma(t) \]

\[ a(t) = -\frac{k}{m} y_m \cos(\omega t + \Phi) \]

We can write for the period of the SHM:

\[ T = \frac{2\pi}{\omega} = 2\pi \sqrt{\frac{m}{k}}. \]

The period of oscillation for simple harmonic motion for a mass–spring system depends on the mass and the spring constant of the spring. In your experiment, the mass will include not only the mass added to the spring (\( m_p \) plus additional mass, \( m \)) but also the effective mass of the spring itself which is some fraction \( f \) of the spring mass \( m_s \). The period is given by

\[ T = 2\pi \sqrt{\frac{m+m_p+fm_s}{k}} \]
For uniform springs, the theoretical value of $f$ is $1/3$. The motion is damped and the amplitude decreases with time, therefore

$$y(t) = e^{-\beta t}y_m \cos(\omega t + \Phi)$$  \hspace{1cm} (7)

where $\beta$ is the damping constant.

An example is given in the following figure.

Under-damped simple harmonic motion

### 2- Experiment

**2-1 Object:** To study Hooke’s law, and simple harmonic motion of a mass oscillating on a spring.

**2-2 Apparatus:** Rotary motion sensor, thin string, uniform spring, balance, weight hanger and weight, computer Pasco Model 700 Interface, printer.
2-3 Procedure:

1- Adjust the apparatus. Setup the apparatus as shown in the figure. The 500 g weight on the right pan goes on the floor that the spring is attached to and on the other pan (that is on left) you put 40 g weight, m_p, so that the spring and the scale are vertical. Take that position of the pan as the equilibrium position.

2- Start the data collection – add extra mass m such as 10g, 20g, 30g and 40g to further stretch the spring. For each extra mass m, allow the pan to go down very slowly to the maximum position x and stop the data collection. Enlarge the position’s table – you can record the extra stretch x. Repeat this with the different weights. Plot mg vs. x, draw a straight line through the origin and all the points. (g is the gravity acceleration constant). The slope of the line is the spring constant k

3- Remove the extra masses and come back to the equilibrium position (with 40g). Displace the whole weight by a small vertical distance (an inch or two). Release the system and start the collection data at the same time. When the oscillations (vibrations) vanish, stop the data collection. On the graph of the position vs. time, use the sine fit to fit all sinusoidal plots. You can read the period of oscillations and calculate the value of the corresponding frequency ω₁. Now, using the formula ω₁² = k/m₁ calculate the real mass m₁. What is your conclusion?

4- Use the computer pencil to draw the line that connects the top peaks of the position’s waves.

5- Use the Natural Exponent fit to fit that line. The exponent C gives you the value of β/2. Infer the value of the damping constant β.
6- Repeat the same experiment for the extra mass of 40 more grams.
7- Print all graphs and tables.
Rotation and Torque (Equilibrium of Rigid Bodies)

Object: To study the use of a balanced meter stick, the concept of torque and the conditions that must be met for a body to be in rotational equilibrium.

Theory: When a rigid body with a fixed pivot point O, is acted upon by a force, there may be a rotational change in velocity of the rigid body. In the diagram below, there is a force $\vec{F}$ that is applied to the arm of the lever. The position relative to the pivot point O is defined by a vector $\vec{r}$. The two make an angle with each other $\varphi$ ($\vec{F}$ is in the plane of the paper). $\vec{F}$ may be resolved into two components. The radial component $F_r$ points along $\vec{r}$ and does not rotate. The tangential component $F_t$ is perpendicular to $\vec{r}$ and has the magnitude $F_t = F \sin \varphi$. This component does cause rotation. The quantity $\tau$ is defined as

$$\tau = (r)(F \sin \varphi)$$

There are two other ways of computing torque,

$$\tau = (r)(F \sin \varphi) = r * F_t$$

$$\tau = (r \sin \varphi)F = r_\perp * F$$

Where we have $r_\perp$ as a perpendicular distance between the rotation axis at the pivot and a line extended from $\vec{F}$. The extended line is the line of action of $\vec{F}$ and $r_\perp$ is the moment arm of $\vec{F}$. Torque means “to twist” and has the unit of N * m. Do not confuse the units of torque with the units of energy as Joule, J is defined as N * m. Torque is defined as positive if rotating counter-clockwise and negative if clockwise. Torque obeys the superposition principle, therefore when several torques act on a body, the net torque or resultant torque is the sum of the individual torques.
The gravitational force on an extended body is the vector sum of the gravitational forces acting on the individual elements of the body. The gravitational force $\vec{F}_g$ on a body effectively acts at a single point, called the center of gravity (COG) of the body. If $\vec{g}$ is the same for all elements of a body, then the body's center of gravity (COG) is coincident with body's center of mass (COM).

We introduce $\lambda$ as the linear density, where $\lambda = \frac{\text{Mass}}{\text{Length}}$.

**Part II**

\[ \tau_L = \tau_R \]
\[ r_1 F_1 = r_2 F_2 \]
\[ M \cdot x_2 \cdot g = M_{\text{stick}} \cdot x_1 \cdot g \]
\[ M_{\text{stick}} = \frac{M \cdot x_2}{x_1} \]

Second method:

\[ \tau_L = \tau_R \]
\[ r_1 F_1 = r_2 F_2 \]
\[ x \left( \lambda \cdot \frac{x}{2} \right) \cdot g + M \cdot x_2 \cdot g = (L - x) \left( \lambda \cdot \frac{(L - x)}{2} \right) \cdot g \]
\[ M_{\text{stick}} = \frac{2 \cdot M \cdot x_2}{L - 2 \cdot x} \]

**Part III**

\[ \tau_L = \tau_R \]
\[ M \cdot x_2 \cdot g = M_{\text{stick}} \cdot x_1 \cdot g + m \cdot x_3 \cdot g \]
\[ m = (M \cdot x_2 - M_{\text{stick}} \cdot x_1) / x_3 \]

**Apparatus:** Meter stick, stand, weight pans, sets of masses, and an unknown weight
Procedure:

Part I
1. Determine the center of gravity by balancing the meter stick on a sharp edge. Repeat several times. Use the value that is the average of the measured values.
2. Weigh the weight holders and label them. Use the average of several readings.

Part II
1. Balance the stick on a sharp edge when a known mass of 50 g is hung from the stick. Do not use the center of gravity of the stick as the balance point or fulcrum. Determine the distance from the center of gravity of the stick to the new fulcrum. Determine the distance from the known mass to the new fulcrum. From the condition of equilibrium for torques, solve for the mass of the meter stick. Repeat at least three times with the 50 g mass hung from different places on the stick. Determine the average and compare it to the value determined by weighing the stick.

Part III
1. Hang a 75 g mass from one hanger and an unknown mass from the second hanger. Balance the meter stick at a position other that the center of gravity. Balance the weight hangers to the fulcrum. Determine the unknown weight using the conditions of equilibrium.

<table>
<thead>
<tr>
<th>Positions</th>
<th>Distance to Fulcrum</th>
<th>Mass of Meter Stick</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50 g</td>
<td>COG 50 g</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Average mass of meter stick: __________

<table>
<thead>
<tr>
<th>Positions</th>
<th>Distance to Fulcrum</th>
<th>Mass of Unknown Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>Unknown 75 g</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
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<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Average mass of Unknown Weight: __________
Questions:

1. Why was the supporting force exerted on the meter stick by the sharp edge not considered in your calculations?

2. A meter stick is pivoted at its 50 cm mark but does not balance because of non-uniformities in its material that cause its center of gravity to be displaced from its geometrical center. However, when weights of 150 g and 300 g are placed at the 10 cm and 75 cm marks, respectively, balance is obtained. The weights are then interchanged and balance is again obtained by shifting the pivot point to the 43 cm mark. Find the mass of the meter stick and the location of its center of gravity.
Archimedes’ Principle

1. Theory
We are aware that some objects float on some fluids, submerged to differing extents: ice cubes float in water almost completely submerged, while corks float almost completely on the surface. Even the objects that sink appear to weigh less when they are submerged in the fluid than when they are not. These effects are due to the existence of an upward ‘buoyant force’ that will act on the submerged object. This force is caused by the pressure in the fluid being increased with depth below the surface, so that the pressure near the bottom of the object is greater than the pressure near the top. The difference of these pressures results in the effective ‘buoyant force’, which is described by the Archimedes’ principle.

According to this principle, the buoyant force $F_B$ on an object completely or partially submerged in a fluid is equal to the weight of the fluid that the (submerged part of the) object displaces:
\[
F_B = m_f g = \rho_f V g .
\]
where $\rho_f$ is the density of the fluid, $m_f$ and $V$ are respectively mass and the volume of the displaced fluid (which is equal to the volume of the submerged part of the object) and $g$ is the gravitational acceleration constant.

2. Experiment
Object: Use Archimedes’ principle to measure the densities of a given solid and a provided liquid. Apparatus: Solid (metal) and liquid (oil and water) samples, graduated cylinder, beaker, thread, balance, weights, stand, micrometer, calipers

Part a.: A solid object of volume $V$, heavier than water. When completely submerged in water, the buoyant force is
\[
F_B = \rho_w V g ,
\]
where $\rho_w$ is the density of water. The mass of the object, $M_o$, when weighed in air is given by
\[
M_o = \rho_s V
\]
where $\rho_s$ is the density of the solid. The apparent weight of the object, $M_w g$, when immersed in water is the difference between its weight in air and the buoyant force:
\[
M_w g = M_o g - \rho_w V g .
\]
Therefore,
\[
M_w = M_o - \rho_w V = M_o - \rho_w \frac{M_o}{\rho_s} \quad \text{(5)}
\]
\[
\rho_s = \frac{M_o \rho_w}{M_o - M_w} \quad \text{(6)}
\]

Part b.: If instead of water, oil is used and the mass of the object of density $\rho_s$ completely submerged in the oil is represented by $M_o$, then
\[ \rho_s = \frac{M_a \rho_l}{(M_a - M_l)} \]  \hspace{1cm} (7)

From Eqs. (6) and (7) we can obtain the density of the oil

\[ \rho_l = \frac{(M_a - M_l) \rho_l}{(M_a - M_w)} \]  \hspace{1cm} (8)

**Procedure:**

1. Determine the density of water and oil. Weigh 100 ml of water and 100 ml of oil. \((\rho = \frac{M}{V})\)

2. Weigh cylinders of aluminum, copper, and iron. Submerge each cylinder in the graduated cylinder filled to 500 ml or less of water.

3. Measure the displaced volume.

4. Calculate the density of the three cylinders. \((\rho = \frac{M}{V})\).

5. Suspend the same solid cylinders from the balance, and weigh it in air and when fully submerged in water.

6. Now weigh the same object when it is fully submerged in oil.

**Calculation:** Perform the following calculations.

1. Use equation (6) and data from procedure (2) to compute the density of the solid object. Compare your answer with the result from task (1) and with standard values.

2. Use equation (7) to calculate the density, \(\rho_l\), of the oil, and compare it with the value measured earlier.

3. Calculate the percent of error for each of your measurements.
1. Theory

Imagine two waves, say simple harmonic motion (SHM, i.e., sine/cosine) waves of identical wavelength and amplitude traveling in opposite directions with equal speeds. The net displacement of the medium at any point and at any time is determined by applying the superposition principle which states that the net displacement is given by the algebraic sum of the two individual displacements. The resulting wave pattern will then have points, separated by one-half wavelength, where the displacement is always zero. These points are called nodes. Midway between this nodes, the particles of the medium located at the antinodes, vibrate with maximum displacement.

![Image of standing waves](image)

Fig. 1: The three lowest frequency for transverse vibrations of a string clamped at the ends.

We can visualize transverse standing waves on a string, of length $L$, fixed at both ends. These waves can be established by plucking the string at some point and are caused by continual reflection of the traveling waves at the boundaries, in this case the two fixed ends. The boundary conditions demand that at each end there must be a node. We can therefore fit an integral number of half-wavelengths into the length $L$ of the string as shown in Fig. 1.

Even though the wave shape is not moving, we can associate a velocity with the standing wave which is the same as that of the traveling wave in the same medium. It can be deduced from Fig. 1, that the wavelengths of the traveling waves that combine to give the standing waves are given by $L = \frac{n(\lambda_n)}{2}$ so that $\lambda_n = \frac{2L}{n}$, where $n$ is an integer. The corresponding frequencies are therefore given by $f_n = \frac{v}{\lambda_n} = \frac{nv}{2L} = nf_0$ with $f_0 = \frac{v}{2L}$, where $v$ is the speed of transverse traveling waves on the string.

The frequencies are known as resonance frequencies of this system. The lowest frequency of the system, having the longest wavelength, is called the fundamental frequency and the mode of vibration as the fundamental mode or the first harmonic. The modes of
vibration with progressively higher frequencies, are called second harmonic \((n = 2)\), third harmonic \((n = 3)\), etc.

Longitudinal standing waves of air columns can also be set up in closed (open at one end, closed at the other) and in open (open at both ends) organ pipes. A longitudinal wave, such as a sound wave, is a wave of density variation. The fixed or closed and of the pipe cannot have any longitudinal motion and is therefore a node of the density wave. The free or open end of the pipe is a position of maximum longitudinal displacement and is therefore an antinode of the density wave.

![Fig. 2: The longitudinal vibrations of air in a pipe, closed at the left and open at the right.](image)

In a closed pipe of length \(L\) the boundary conditions require that the closed end be a node and the open end an antinode. We can therefore fit an odd multiple of quarter-wavelengths into the length \(L\) of the pipe as shown in Fig. 2.

The transverse wave pattern for the standing wave for the standing waves are displayed in this figure. The wavelengths of the traveling waves that combine to give the standing waves are given by \(L = \frac{n\lambda}{4}\), i.e., \(\lambda = \frac{4L}{n}\) where \(n = 1, 3, 5, \ldots\). The corresponding resonance frequencies are therefore given by \(f_n = \frac{v}{\lambda_n} = \frac{v}{4L} = nf_0\) with \(f_0 = \frac{v}{4L}\), where \(v\) is the speed of longitudinal traveling waves (sound) in air. It is to be noted that the closed organ pipe will support only odd harmonics. The frequency of the first harmonic or the fundamental frequency of equals \((\frac{v}{4L})\).

For an organ pipe in which both ends of the pipe are open the situation is the same as for a string with its two ends fixed except that both the ends are now antinodes for any standing harmonic wave. The wave patterns therefore will yield the resonance frequencies as \(f_n = n\frac{v}{2L} = nf_0\) with \(f_0 = \frac{v}{2L}\). It is seen that the open organ pipe will support all harmonics.

For a given frequency, the first resonance corresponds to the length of the closed-end air column equal to \(\frac{\lambda}{4}\). The second resonance corresponds to \(\frac{3\lambda}{4}\). The difference between these positions would correspond to half a wave length. The sound velocity is determined from \(v = f\lambda\) where \(f\) is the tuning fork frequency in Hertz. At room temperature \(T\) (in degrees of Celsius), the theoretical value of sound velocity (in m/s) is \(v = 331+0.61T\).
2. Experiment

Object: To determine the speed of sound in air using resonance of a close-end air column.

Apparatus: Resonance tube apparatus, tuning fork, rubber mallet and a Macintosh Computer.

Procedure:

1. Strike a tuning fork of frequency 512 Hz with a rubber mallet and hold it at about an inch above the open end of the resonance tube with its prongs horizontal. Adjust the water level starting from its highest level. Gradually increase the length of the air column by lowering the can to find the first position of resonance, where the sound coming out of the air column is loudest. You may have to strike the fork several times and move the water column up and down to precisely locate the resonance position.

3. Continue this procedure to find second (and if possible, the third) position of resonance. Record these lengths as $l_1$ and $l_2$.

4. Repeat the experiment with a tuning fork of different frequency.

Calculations: Using the computer spreadsheet perform the following calculation.

1. Calculate the speed of sound from the formula $v = \lambda f = 2(l_2 - l_1)f$, where $f$ is the frequency of the tuning fork.

2. If you get only the first resonance, and not the second resonance then, to calculate the speed of the sound, use $v = 4fl_1$.

3. Compare the calculated speed of sound with the theoretical value from the formula $v = 331 + 0.61T$, where $T$ is the room temperature in Celsius degrees.

Questions:

1. Sketch the air column vibrations for third resonance. What is the difference between the positions of the third and the first resonance in terms of wave length?

2. Should the velocity of sound in air depend upon the frequency of the tuning fork?
3. Are there “anti-resonances” where the sound coming out of the air column reaches minimum? What is the length of air columns for these “anti-resonances”?
4. Why does the resonance position correspond to the “loudest sound”?
5. Do you see any advantage of \( v = f(l_2 - l_1) \) over \( v = 4fl_1 \)?
Specific Heat of Solids

**Object:** To determine the specific heat of a given solid specimen.

**Theory:** Thermal energy is an internal energy that consists of the kinetic and potential energies associated with the random motions of the atoms, molecules, and other microscopic bodies within an object. If there is an environment with temperature \( T_E \) and a system with temperature \( T_S \), then the two will reach thermal equilibrium \((T_E = T_S)\) if given enough time. The transfer energy is called heat and has the symbol \( Q \). Heat is positive when absorbed and negative when lost. Heat is the energy that is transferred between a system and its environment because of the temperature difference that exists between them. The SI unit for heat is the Joule, \( J \). The British thermal, \( BTU \) unit is defined as the amount of heat to raise 1 lb of water from 63\(^\circ\) F to 64\(^\circ\) F. The calorie is defined as the amount of heat to raise the temperature of 1 gm of water 1\(^\circ\) C.

\[
1 \text{ cal} = 3.969 \times 10^{-3} \text{ BTU} = 4.1860 \text{ J}
\]

Heat capacity \( C \) of an object is the proportionality constant between the heat and the temperature change.

\[
Q = mC\Delta T
\]

Specific heat is defined as heat capacity per unit mass, \( C \).

If we have two objects of different material and temperature, according to the conservation of energy then

\[
\Delta Q_{\text{lost}} = \Delta Q_{\text{gained}}
\]

\[
m_sC_s\Delta t = m_wC_w\Delta T
\]

\( m_s \) is the mass of the metal solid, \( C_s \) is the specific heat of the metal solid, and \( \Delta t \) is the change in temperature of the solid. \( m_w \) is the mass of the water, \( C_w \) is the specific heat of the water, while \( \Delta T \) is the change in temperature of the water.

\[
C_s = \frac{m_wC_w\Delta T}{m_s\Delta t}
\]

\[
C_s = C_w \frac{m_w}{m_s} \left( \frac{T_f - T_i}{t_i - t_f} \right)
\]

Since the metal solid will be cooled and its final temperature will be less than its initial temperature we write \( \Delta t \) as \( t_i - t_f \). Also, it is assumed that none of the heat is lost to the surroundings.

**Apparatus:** Double boiler, styrofoam calorimeter, one Celsius thermometer along with a temperature sensor (for the computer), metal cylinder, metal cup with handle, and a mass-balance.
Procedure:
Fill the double-boiler approximately three-quarters full of water, and start heating it.

1. Place 50 ml of water into the styrofoam calorimeter. (50 ml of water is equivalent to 50 grams of water, so \( m_w = 50 \) grams)
2. Put the temperature sensor into the Styrofoam calorimeter and monitor the computer until the temperature is stable this is \( T_i \) (initial temperature of water).
3. Weigh the metal cylinder and record \( m_c \). Place a metal cylinder inside a metal cup with handle along with water until the metal is half full. Then partially immerse the metal cup in water that is inside the boiler but do not warm it above approximately 96 to 98˚C, but please not above 98˚C. Record the stable temperature, \( t_i \).
4. Move the metal cylinder from the metal cup with handle using the string provided and place the metal cylinder in the Styrofoam calorimeter and gently stir the water while keeping an eye on the thermometer and monitor the temperature. Record the highest temperature reached which is the final equilibrium temperature which will be \( T_f \) which equals \( t_f \).
5. Calculate the specific heat of the metal cylinder from the data and then compare it with the standard value to find the percentage error.
6. Repeat the process for each of three metal cylinders indicated in the table below. Be SURE to use a new fresh cool 50 ml water sample for each metal cylinder experiment.

### Table

<table>
<thead>
<tr>
<th>Material</th>
<th>( c ), specific heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>( 452 ) K * kg</td>
</tr>
<tr>
<td>Aluminum</td>
<td>( 900 ) K * kg</td>
</tr>
<tr>
<td>Copper</td>
<td>( 386 ) K * kg</td>
</tr>
<tr>
<td>Water</td>
<td>( 4186 ) K * kg</td>
</tr>
</tbody>
</table>

**Question:** What are the assumptions made in the experiment?
Thermal Expansion

**Objective:** To measure the coefficient of linear expansion for given material.

**Theory:** Most substances expand with an increase in temperature. With added, the atoms can move a bit farther from each other than usual, against the spring-like interatomic forces that hold every solid together. The change in length of a solid is proportional to its original length and to the change in temperature.

\[ L_2 - L_1 = \alpha L_1(T_2 - T_1) \]

\[ \Delta L = \alpha L_1 \Delta T \]

The proportionality constant \( \alpha \) is called the coefficient of linear expansion. The coefficient has the unit “per degree” or “per Kelvin” and is depends on the material. The coefficient of linear expansion \( \alpha \) may be expressed as

\[ \alpha = \frac{L_2 - L_1}{L_1(T_2 - T_1)} = \frac{\Delta L}{L_1 \Delta T}. \]

Where \( L_1 \) is the original length in meters at the temperature \( T_1 \) °C, \( L_2 \) is the length at temperature \( T_2 \) °C. The change in length will be measured by a dial indicator gauge.

**Apparatus:** Linear expansion apparatus, voltage source, metal rod(s), tubing, meter stick, boiler, heater, drainage dump, and Data Studio.

**Procedure:**
1. Add water to boiler, turn on boiler, and insert the rubber stopper.
2. Open Data Studio and select the file thermal_expansion.ds and open it.
3. Select one rod to mount on the linear expansion apparatus. Measure the length of the rod and mount the rod on to the apparatus. (Tighten the screw at end of the rod to hold into place)
4. Zero the dial indicator gauge. (Make sure that the gauge is in contact with the lever arm that is attached to the rod.)
5. Attach thermistor to rod. (Figure 2)
6. Click start on the data studio platform. Record the initial temperature.
7. Connect the hose to the boiler and to the rod. On the other end of the rod attach the drainage dump. (Figure 1)
8. The steam from the boiler will travel through the rod into the drainage dump. DO NOT TOUCH THE ROD. Record the change in temperature indicated by the plateau shown in Data Studio.
9. Record the change in length shown by the dial indicator gauge.
10. Using the measured results calculate the coefficient of linear expansion \( \alpha \), for the material. Find percent error from standard value given.
11. Repeat steps 3-9. (Let rod cool before changing the rod for another rod of different material)
12. Dismantle the equipment and dry the rod, tube and tubing.

<table>
<thead>
<tr>
<th>Material</th>
<th>Brass</th>
<th>Copper</th>
<th>Steel</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>α (°C⁻¹)</td>
<td>19 \times 10^{-6}</td>
<td>17 \times 10^{-6}</td>
<td>11 \times 10^{-6}</td>
<td>23 \times 10^{-6}</td>
</tr>
</tbody>
</table>

![Figure 1](image1.jpg)
![Figure 2](image2.jpg)
![Figure 3](image3.jpg)