The laboratories are an essential part of your learning of key physical principles. The labs in this manual have been assembled to complement the discussions of motion, forces, waves and thermodynamics from the Physics 131 lecture sessions. Since they are an essential part of your learning experience, we expect students to complete all of the laboratory assignments.

In the event of a lab missed due to illness or other difficulty, makeup labs can be scheduled provided they are carried out within two weeks of your return.

Acknowledgements

These labs have been collected, and re-written over the course of several years, and only a partial list of credits is given here. The Data and Calculations lab was written by Bob Cadmus. The Introduction to Motion, and Velocity and Acceleration labs are from the Tufts University “Tools for Scientific Thinking” project, and were written by Ronald K. Thornton (Tufts University) and David R. Sokoloff (University of Oregon and California Polytechnic State University). Moment of Inertia lab was rewritten by Paul Weber. The cover illustration (falling golf balls, without and with initial horizontal velocity) was taken from Halliday, Resnick and Walker, Fundamentals of Physics (5th ed).
Introduction to Motion

Introduction

In this lab you will use an ultrasonic range finder to determine the distance as a function of time from the ultrasonic transducer to you (as a reflector of sound waves). The equipment (Lab Pro) is connected to a computer with software (*Logger 3.0*) that can produce tables and graphs such as position versus time or velocity versus time.

There are a variety of “experiments” possible with this equipment that should solidify your understanding of motion. In this handout we’ll suggest several that will aid in understanding the operation of the system. Then, you should construct other options that are appealing to you.

Getting Started.

Click on the 01a Graph Matching icon to enter the program.

When you are ready to start graphing distance, click once on the Collect button at the upper right of the screen. Pressing the F11 key performs the same function. The system works by detecting reflected sound waves. Reflections occur from objects directly in front of the detector, including your arms - don’t swing your arms as you walk.

Walk in front of the detector to get a feel for how the system works. Are the distances reasonable? What are the maximum and minimum limits of the range of the detector? Note: seemingly insignificant objects can reflect the sound wave and lead to false readings. See what the detector will respond to (tablet, hand, pen)

Useful Tools: Across the top of the graph is a menu of useful tools. By pointing with the cursor you can find out what they are. At this point the following may be useful.

*Auto scale* – This will adjust the vertical scale of the graph to best display the curve.
*Zoom In* – By first selecting a section of the graph, this will allow one to expand this section.
*Zoom Out* – Undoes “Zoom In”.
*Examine* – This allows one to directly read numerical values from the graph.

The scale of the graph can also be changed by clicking directly on the graph and changing the details in the dialog boxes. A third option is to click on the highest or lowest value of a scale and change it directly.

Make some distance - time graphs for different walking speeds and directions just to see if the system is working correctly.
Distance - time graphs

The following three graphs show distance versus time plots. Duplicate these plots in Logger by walking in front of the detector. Draw the curve and explain what you did to reproduce the curves in your lab notebook.

Now, draw some more imaginative curves and reproduce these as well.

Velocity - time graphs

You can also make velocity versus time graphs with Logger. Click on the ‘Position’ label on the vertical axis. When the menu appears select velocity. Set the Velocity axis from -1 to 1 m/sec. Also change the Time axis to read 0 to 5 sec. This is done by clicking on the highest value on the time scale and changing it to 5. You will want to change the period of the data collection as well. Go to ‘Experiment’ and select “Data Collection”. Change the “Length” to five seconds.

The following three graphs show velocity versus time plots. Duplicate these plots in Logger by walking in front of the detector. Draw the curve and explain what you did to reproduce the curves in your lab notebook.

Now, draw some more imaginative velocity versus time curves and reproduce these as well.
Distance / Velocity Graphs

Add a second graph to the display. This is done by clicking on ‘Insert’ in the tool bar and selecting ‘Graph’. To make things look nice go to ‘Page’ and select ‘Auto Arrange’. Change the vertical axes if necessary till you have two graphs, one of ‘position’ vs. ‘time’ and one of ‘velocity’ vs. ‘time’.

As before, walk in front of the motion detector producing graphs of position and velocity vs. time.

Select the position vs. time graph and click on the ‘Tangent’ tool in the Tool bar. As you scan over the time scale do you see the relation of the readings with the velocity vs. time plot? The ‘Tangent’ can be removed by again clicking on the tool.

Select the velocity vs. time graph and select a section of this graph by dragging with the mouse. Next use the integration tool. Do you see the relation between this numerical value and the position vs. time graph? Make sure you are clear on the point of this section before you leave the lab.

Some interesting questions

What if the sound wave reflector remained fixed and you moved the source? Would your curves change?

Does the value of the speed of sound influence the graphs? Often with such questions, it’s appropriate to consider extreme situations; for example, if the speed of sound were very low, say 1 meter per second, how would your graphs change?

Can you think of other interesting experiments (or practical uses) for this equipment?
Velocity and Acceleration

In this lab we continue our study of kinematics, the description of motion. We will again use the motion detectors and the Logger Pro program. To start the program, click on the ‘Cart’ icon. This will allow the program to display Position and Velocity.

1. Motion of the cart on a level surface. For this part lay the board flat against the table. It is not important that the surface be exactly flat or level. Place the motion detector on the table about 20 cm away from the end of the board. This way the cart is less likely to slam into the detector. They are fragile and expensive! Gently push the cart away from the detector and record the data. The section of the graph that is of interest is between when the cart was released and when it hit the stop. Can you identify that section? It may take some practice. Note: The motion detector can be easily fooled and give the distance to something else other than the cart.

Logger Pro has several tools that make it possible to study sections of the motion.

1) Zoom In. With the mouse select a section of the graph. Note: zoom selects a vertical as well as a horizontal section on one of the graphs. Now click on ‘Zoom In’ on the tool bar. ‘Zoom Out’ goes back.

2) Linear Fit / Curve Fit. Select a section of a graph. If one now clicks on ‘Linear Fit’ the program will generate an equation for a straight line that most closely matches the section curve. If no section is selected it fits the entire curve. Curve Fit is similar but gives a number of options such as a quadratic or parabola that can be used for the fit.

3) Tangent. This was discussed in the previous lab and gives a fit at a point that is similar to the Linear Fit.

How would you describe the motion in this example? Is it similar to any standard examples seen in class?

2. Motion of the cart on an incline. Raise one end of the board by about 10 cm. Place the motion detector on its side at the top of the board. Allow the cart to start from rest and run down the board while you collect data. How would you describe the resulting motion? It is one of the standard motions you saw in class. Fit the curves to the to the Position and Velocity graphs. Show that they are consistent. It is also possible to add a third graph. Under ‘Insert’ on the tool bar, select ‘Graph’. Then under ‘Page’ select ‘Auto Arrange’. Set this third graph to show acceleration. Does this graph agree with your curve fits above?

Next start the cart by gently pushing it towards the detector. This will take some care; you don’t want the cart to come too close to the detector because of its minimum range of about 50 cm and you don’t want the cart to hit the detector. Carry out the same analysis as before. Is the acceleration the same? What is the velocity when the cart is closest to the detector? What is the acceleration at this same point?
This is a good point to check something we looked at in the last lab. Remove all of the curve fits from the graphs. This is done by clicking on the orange squares at the upper left of the boxes. (The targets are quite small.) Using the ‘Tangent’ and ‘Integral’ tools show that the proper relations exist between the Position, Velocity and Acceleration graphs.

3) **Motion of the coffee cup cylinder on an incline.** Remove the acceleration graph. This done be clicking on the graph and hitting delete key. Allow the cylinder to start from rest and roll down the plane. Describe the motion using the tools discussed above. Next start with the cylinder rolling up the incline toward the detector. Again describe the motion.

4) **Falling Objects.** Carrying out the measurements in this section will require extra care and several tries. Place the motion detector on the floor facing upward. **Important!** Place the protective wire cage over the detector. The detector should be away from the tables and chairs to avoid false readings. Start the ‘Collect’ and drop a tennis ball directly on the detector cage from about 2 m. Can you measure a good value for the free fall acceleration of gravity?

Perform the same experiment with a very loosely wadded piece of paper. Here on would expect the paper to approach a terminal velocity. What is it? If you look carefully at the velocity curve just after the paper was released you should be able to see the free fall acceleration of gravity. Can you measure it?

There are lengths of felt material in the lab. You can modify any of the cart experiments by placing the felt over the board and repeating the experiment. How are these results different from your earlier results?
**Projectile Motion on an Air Table**

Imagine that you are a “flatlander,” a person confined to two dimensions, and your world is the tilted air table. In your world objects (pucks) fall when released, and the direction in which they naturally fall is down to you. Your goal is to understand the physics of projectile motion in your world.

You make two kinds of measurements: (1) You take the puck to a high location and let it fall freely, with the spark making dots as it falls. (2) You shoot the puck up at an angle and watch it go up and then back down. Do both these things using the same sheet of paper. Now draw a line parallel to the line of dots made when the puck fell freely and call that the y-axis; draw another line perpendicular to the y-axis and call it the x-axis.

**Find the acceleration of a freely falling body in your world.**

If the spark timer has produced 20 spots per second, circle alternate spots and use only 1/10 second intervals. For each pair of spots on the path of the projectile falling “straight down,” compute the average speed by dividing the distance between the pair by 1/10 second. Now plot the average speeds against time and from the slope of the best straight line through the average speed points compute the acceleration. Use Excel as much as possible.

**Study the motion of a projectile in your world.**

For the projectile motion also use only spots 1/10 second apart. For each pair of spots, calculate the average x- and y- components of the velocity \((v_x \text{ and } v_y)\) by dividing the x or y distances between the spots by 1/10 second. (It may be faster to project all the dots onto the x and y axes. If you do that, use differently colored marks on the y-axis for the dots rising and descending.) Now plot the average velocities against time, remembering that you will have both positive y velocities (puck rising) and negative y velocities (puck descending). From the slope of the best straight line through the average velocity points compute both the x and y accelerations.

Determine whether the x-component of velocity of a projectile is constant in your world.

Determine whether the vertical acceleration of a freely moving body is the same when the body has a horizontal component of velocity as when it does not.

What is the acceleration of a projectile thrown straight up at the time when its velocity is zero at the top of its flight? This can be answered either by doing another experiment or by reconsidering the data you already have.
Forces and Motion

This experiment is an investigation of a simple physical system in which you will try to reconcile any discrepancies between experimental measurements and a theoretical model.

The Experiment:

With the air table level, attach a light cord to the air puck, pass it over the pulley on the edge of the table, and hang a mass on the other end. Appropriate masses are 10 g, 20 g, and 50 g. Let the falling mass draw the puck across the table, leaving a line of spark points. On the same sheet of paper, make one record with each of three different masses. Then, select one of the three masses and make an additional record.

The Analysis:

From your data, determine the velocity of the puck as a function of time. Draw an appropriate graph and determine the acceleration. (Is it constant?) Use Excel as much as possible.

Determine how the puck should move based on what you have learned in the course, assuming that friction is negligible. Choose three sets of data, each for a different mass. Do your experimental and theoretical results agree? That is, are the errors you can reasonably expect in your measurements large enough to account for any discrepancies? In discussing this point, be as quantitative as possible. It is often difficult to reliably estimate expected errors. One method of determining a minimum expected error is to repeat the measurement for one of the masses and see how close the new results are to the previous results. Depending on the remaining time, you can make this comparison using your fourth data set.

What factors or assumptions affect the comparison of theory with the results of this experiment and how? How would they change from one mass to another? What experimental tests could you perform to test the validity of these assumptions?
Centripetal Force

In this experiment we treat a mass hanging on a centripetal force rotor apparatus as an unknown quantity, and determine its value by measuring the inward/axial force that acts on it while it is spinning. This is a centripetal force – it causes a centripetal acceleration that keeps the mass moving in a circle in the horizontal plane.

Practice spinning the rotor until you acquire the knack of keeping the speed (and hence the radius of the circle described by the hanging mass) constant for many rotations. Then determine the time required for one rotation at the set radius by counting and timing many rotations. From the period and the radius, compute the centripetal acceleration.

The centripetal force acting on the mass when it is rotating is provided by the stretched spring. The magnitude of this force can be determined by stopping the rotation, pulling the mass out to the radial position it occupied during rotation, and measuring the force required to hold it in equilibrium in that position. This outward pull must equal the centripetal force produced by the stretched spring during rotation. Use this method to determine the centripetal force, which was acting on the mass while it was rotating.

Use the measured centripetal force and the computed centripetal acceleration to determine the mass of the bob. Estimate uncertainties in the measurements contributing to this determination, and compute the uncertainty in the value of the mass. One way to compute this uncertainty is to determine or estimate the maximum and minimum values of each of your measured quantities and use these to determine the upper and lower limits to your mass measurement.

Finally, use one of the balances provided to measure the mass directly. Compare with your computed value.
Measurement

How tall are you?

How fast is that ball moving across the floor?

These questions will provide the framework for our introduction to the concept of measurement. Although measurements are often summarized by a final numerical value accompanied by a range of experimental uncertainty, these numbers imply the use of a carefully designed measurement process – whether or not that is actually the case! For your measurements, of course, it will always be true. Right?! In any case, as we perform experiments this semester your lab book will be the place for you to justify what you are doing. If anyone doubts your measurements, you’ll have a record to back up your claims. This first meeting of the laboratory should be thought of as an exercise in measurement with participatory discussion and agenda lead by the instructor.

Near the end of the period, you will be asked to respond to the following question in the space below:

What is measurement?
Two-Dimensional Collisions: Part I

In this experiment you will examine the collision of two steel pucks where the external interference is reduced to a minimum. You can achieve this by using the air table where each puck leaves a trail of points from the carbon paper placed under the newsprint. The pucks are launched by hand so that they collide near the center of the table. Note that the points produced by the high voltage are made at the same time for both pucks.

Recommendations:

- Use a spark frequency of 20 Hz.
- Manually smooth the newsprint to eliminate small bumps that might interfere with the motion.
- Make sure the rubber tubing does not become entangled during the motion.
- Do a number of practice runs first.
- Press the foot pedal immediately after you release the pucks. WARNING: If you press the pedal early, you will give yourself a shock. And, hold down the pedal through the entire collision until the pucks strike the edge of the table.
- When you remove the newsprint from the table and look at the marks, remember that right and left are reversed as the newsprint is turned over.

Collisions:

Generate a collision near the center of the table using two pucks. Don’t be so vigorous as to allow the pucks to tip when they strike each other.

Analyses:

Using a straight edge, draw lines through the paths of both pucks before and after the collision. These points should lie on four straight lines. Since the high voltage is applied between the two pucks, pairs of points are made at the same time. By examining points near the point of collision, determine which pairs belong together. Draw straight lines between all points which occurred at the same time.

Locate the center of mass on the newsprint for each simultaneous pair of points. Does the motion of the center of mass agree with your expectations?

Define your y axis as a line parallel to your center of mass line. Construct a perpendicular as your x axis. Now, determine the x- and y- components of the velocity of the center of mass. Extend the straight lines corresponding to the four puck paths to the x and y axes and measure the angles between these lines and the axes. Determine the x and y components of each of these four velocities.
Determine the momentum vectors of each puck both before and after the collision. To what extent is momentum conserved in the collision? Is the result in agreement with your expectations? Why? Under what circumstances is momentum conserved in a collision?

Determine the kinetic energy of each puck both before and after the collision. To what extent is kinetic energy conserved in the collision? Is the result in agreement with your expectations? Why? Under what circumstances is kinetic energy conserved in a collision?

(To be continued next week with different types of collisions)
Two-Dimensional Collisions: Part II

In this experiment you will examine the collision of two steel pucks where the external interference is reduced to a minimum. You can achieve this by using the air table where each puck leaves a trail of points from the carbon paper placed under the newsprint. The pucks are launched by hand so that they collide near the center of the table. Note that the points produced by the high voltage are made at the same time for both pucks.

Recommendations:

• Use a spark frequency of 20 Hz.
• Manually smooth the newsprint to eliminate small bumps that might interfere with the motion
• Make sure the rubber tubing does not become entangled during the motion
• Do a number of practice runs first
• Press the foot pedal immediately after you release the pucks. WARNING: If you press the pedal early, you will give yourself a shock. And, hold down the pedal through the entire collision until the pucks strike the edge of the table.
• When you remove the newsprint from the table and look at the marks, remember that right and left are reversed as the newsprint is turned over.

Collisions:

Select two of the following configurations for collisions and subsequent analysis

• Pucks of unequal mass
• Pucks with Velcro collars
• Magnetic pucks

Analyses:

Using a straight edge, draw lines through the paths of both pucks before and after the collision. These points should lie on four straight lines. Since the high voltage is applied between the two pucks, pairs of points are made at the same time. By examining points near the point of collision, determine which pairs belong together. Draw straight lines between all points which occurred at the same time.

Locate the center of mass on the newsprint for each simultaneous pair of points. Does the motion of the center of mass agree with your expectations?

Define your y axis as a line parallel to your center of mass line. Construct a perpendicular as your x axis. Now, determine the x- and y- components of the velocity of the center of mass. Extend the straight lines corresponding to the four puck paths to the x and y axes and measure the angles between these lines and the axes. Determine the x and y components of each of these four velocities.
Determine the momentum vectors of each puck both before and after the collision. To what extent is momentum conserved in the collision? Is the result in agreement with your expectations? Why? Under what circumstances is momentum conserved in a collision?

Determine the kinetic energy of each puck both before and after the collision. To what extent is kinetic energy conserved in the collision? Is the result in agreement with your expectations? Why? Under what circumstances is kinetic energy conserved in a collision?
Moment of Inertia

The purpose of this laboratory is to determine the moment of inertia of two spinning masses in a rotor system by measurement and by calculation.

Measurement of Moment of Inertia

Measure “I” for your rotor system of two spinning masses held by a spinning rod and inner cylinder by dropping a known mass through a known distance. By measuring the fall time, you can determine the average velocity of the falling mass and thus can determine the final velocity of the mass just before the mass strikes the floor. Then, assuming conservation of total mechanical energy during the fall, you can determine the moment of inertia (or rotational inertia) of the rotating system. Don’t forget that both the rotating system and the falling mass carry kinetic energy.

Hints: Make careful distance measurements using the Vernier calipers where appropriate. Make several measurements of the fall time so you can use an average value. After you derive an expression for the moment of inertia that depends on the fall distance and fall time, you may wish to enter this formula into an Excel worksheet to make the calculations easier.

Calculations of Rotational Inertia (or Moment of Inertia)

Calculate I for the rotor system, first by approximation as two simple point masses; and second by refining your calculation to include the rotational inertia of the (threaded) cross rod; and third by allowing for rotation of the heavy metal cylinders (no longer treating them as point masses). In the third case you should determine the moment of inertia by direct integration over the volume of the cylinder. You can set up the integration as a one-dimensional situation. What do you notice about the relative size of these terms? You could use a table, listing these three components, their totals, and also the percentage contributions of each component to the total. The contribution to the total rotational inertia from the metal spindle is quite small (if you want to try a calculation, you should assume a mass of 500 grams).

Be sure to compare the measured and calculated moments of inertia.

Calculate where the energy goes in this system. How much of the original potential energy ends up as linear KE of the falling mass and how much ends up as final rotational KE of the rotor system, and how much was lost to friction (is it even possible to estimate the work done by friction from your data???). What are the percentages of each?
Simple Pendulum

Just how simple is a “simple pendulum?” The usual expression for the period:

\[ T = 2 \pi \sqrt{\frac{\ell}{g}} \]

involves some approximations. One approximation is that the amplitude of the swing is small. Another is the assumption that air resistance is negligible. If these approximations are valid, the relationship among the pendulum’s length (\( \ell \)) its period (\( T \)), and the acceleration of gravity (\( g \)) is indeed simple. In that case a pendulum might provide a reasonable method for determining \( g \).

In this lab we will approach the simple pendulum from two distinct points of view. First we will use it measure \( g \); then we will investigate the validity of the equation above. (Strictly speaking, we should investigate the equation’s validity before using it, but the backwards approach is more practical in the lab.)

I. Measure \( g \) using a pendulum. Before you begin, think about how the length of the string and the number of periods observed affect the uncertainty in the measured value of \( g \). Determine \( g \) as accurately as you can, and estimate the uncertainty in your result! Also compare your result with the “accepted” value of \( g \) and the values you have obtained in previous experiments.

II. Use pendula of different lengths to investigate the dependence of \( T \) on \( \ell \). Plot your data in a way which makes the relationship clear. (Don’t just plot \( T \) vs. \( \ell \) !). Use Excel for plotting.

III. The equation above does not contain the mass of the bob because air resistance has been neglected. Investigate the validity of this assumption by using pendulum bobs of different masses.

IV. The simple equation above is valid if the amplitude of the pendulum’s swing is “small.” The expression:

\[ T = 2 \pi \sqrt{\frac{\ell}{g}} \left( 1 + \frac{1}{4} \sin^2 \frac{\theta}{2} + \ldots \right), \]

where \( \theta \) is the angular amplitude of the oscillation, is more accurate for larger amplitudes. Try to measure the dependence of \( T \) on \( \theta \). Are your results consistent with the “simple” expression? Are they consistent with the “improved” expression?
Waves on a String and Vibrations

The equipment used in this experiment is a string driven by a small oscillating bar as shown below. The frequency (f) of the driver is fixed at 120 Hz.

Since the right end of the string is fixed, waves traveling to the right are reflected and standing waves are formed. The distance between nodes is equal to 1/2 the wavelength. (Note that the point where the string is attached to the bar is not a node.)

Measure the wavelength (λ) for several tensions (T). This may require some adjustment of the spacing between the oscillating bar and the pulley in order to get a usable amplitude. (Question: Will such adjustments change the wavelength?) Plot $\lambda^2$ vs. the tension. Using the graph, find the mass per unit length (μ) of the string. The following relations may be useful:

\[ v = \lambda f \]
\[ v = \sqrt{\frac{T}{\mu}} \]
Vibrations

Simple harmonic motion is one of the most important ideas in mechanics (precisely because it IS simple). Furthermore its ideas are directly carried into atomic and nuclear physics – molecules and nuclei vibrate, atoms are bound in solids by restoring forces which can often be well-described by an appropriate spring constant, etc.

If you thoroughly understand the ideas of simple harmonic motion, you can understand all oscillatory motions because any complicated oscillation can be thought of as a linear superposition of various simple harmonic motions.

In this lab we would like everyone to analyze a real situation in simple harmonic motion using the LabPro equipment.

Select “Logger Pro” - You should see three graphs with a data box to the left. Select the data box and delete it. Select ‘Auto Arrange’ under ‘Page’ to make the graphs look nice. The graphs can be reduced in number by a similar method. To add graphs go under ‘Insert’. Options such as ‘Linear Fit/Curve Fit’ introduced in the Velocity and Acceleration’ lab are available here.

LoggerPro Force Probe and Calibration

Be sure to calibrate the force probe before you use it. Under ‘Experiment’ select ‘Dual Range Force’. You will be asked to apply two known forces. One can be zero. The Motion Detector is placed directly below the mass. Make sure it is protected by its cage.

Measurements

- Determine the spring constant (the k in F = - k x) by creating a graph in LoggerPro of force versus distance. You can measure the distance by placing the motion detector on the floor under the spring. Then, just place your hands over a pencil extended through the end of the spring to present a flat surface to the motion detector; slowly extend the spring after you ask LoggerPro to acquire data. Show the graph of force versus distance (make sure the sign of the slope is correct - it should be a line with negative slope) and ask LoggerPro to fit a straight line to the graph. The spring constant is the magnitude of the slope.

- Set the spring and 350 gram mass in motion. You should measure the displacement, velocity, and acceleration of the mass as well as the force of the spring on the mass. Think carefully about the force. Does the force probe directly measure the force on the mass? If you do not see the data on the graph, you may have to change the y-axis scales (double click on the graph to see the menu to change the axes). You can also use ‘Autoscale Graph’ under ‘Analyze’.
• Measure the period of the motion. Is the period in agreement with your expectations? Could you use this method to measure an unknown mass? Compare the graphs in detail. Do they have the relative phases that you would expect?

• Bring a 350 gram mass to equilibrium at the end of the spring. Now, you can add a negative offset to the distance and force measurements so that the distance and force measurements are zero when the mass is at equilibrium. This is done by selecting ‘Zero’ under ‘Experiment’ when the mass is in equilibrium (at rest).

• Eliminate two of the graphs so that you have only one. Look at plots of Force vs. Position, Force vs. Velocity and other pairs of the four basic quantities Force, Position, Velocity, and Acceleration. Do these graphs appear as circles (with appropriate choice of scales on the axes) or straight lines? Why?

• There are other possibilities, such as taping a cardboard square on the bottom of the mass to create air resistance and viewing the motion over a longer time. Or, you could set up a non-linear oscillator by “tying off” part of the spring (there is a neat way to do this).
Absolute Zero

In the late 1700s Jacques Charles showed that for a gas at constant pressure

$$V \propto (T + c), \text{ (constant pressure)}$$

where $V$ is the volume of the sample and $T$ is the temperature. “$c$” is a constant which depends on the temperature scale you use. This is known as Charles’s Law. It says that volume is a linear function of temperature. Since negative volume makes no sense, this expression implies a lowest possible $T$. We will attempt to determine this minimum $T$, which is known as absolute zero.

To aid in this process, we use Boyle’s Law, which states

$$V \propto 1/P \text{ (constant temperature)}$$

“$P$” is the pressure of the gas. The relationship

$$V \propto (T + c)/P$$

satisfies both of these laws. Multiplying both sides by $P/V$, we find

$$P \propto (T + c)/V, \text{ and if } V \text{ is constant,}$$

$$P \propto (T + c) \text{ (constant volume)}$$

suggesting that the pressure reaches zero at the same temperature for which $V$ becomes zero in Charles’s Law.

Procedure

In the lab, you will find several constant volume vessels with pressure gauges attached. There are also several liquid baths, each at a known temperature. The pressure of your sample of gas at a given temperature can be found by immersing your sample in the appropriate bath. By plotting $P$ vs. $T$, you can determine the value of absolute zero.

Should results depend on the amount or type of gas in your vessel? There are vessels with varying amounts and types of gas available in the lab. Test for these effects. What effect should the gas in the neck have? (should it make your result too high or too low? Why?) How accurate can you expect your result to be, based on an analysis of your procedure?
APENDIX A: Learning to Use Microsoft Excel

In the Physics 131 laboratory we use the Excel-98 version of Microsoft Excel. The comparable version on a PC is Excel-97. All campus computers have these versions available.

Numbers and Graphing

A great deal of science depends on quantitative (i.e. using numbers and equations) descriptions and graphs of those numbers and equations. Manipulations of large sets of numbers and making graphs used to be quite tedious, but computers now make this quite simple. You will learn to use a computer program (a spreadsheet to be specific) called Excel to handle numbers and make graphs. A spreadsheet is a program that holds a potentially huge table of facts (numbers or words/short phrases/symbols). It allows you to keep track of those facts, graph the number parts, and do arithmetic and sorting of those facts.

To help you get started with this, we'll use a silly example to give you some data to graph. A group of Physics 131 students went on a picnic, and that picnic included a running backwards race with several grade schoolers. Here are some times for the race, in seconds:

<table>
<thead>
<tr>
<th>Name</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>James</td>
<td>17</td>
</tr>
<tr>
<td>Mary</td>
<td>19</td>
</tr>
<tr>
<td>Tim</td>
<td>13</td>
</tr>
<tr>
<td>Joshua</td>
<td>14</td>
</tr>
<tr>
<td>Hannah</td>
<td>38</td>
</tr>
<tr>
<td>Robbie</td>
<td>96</td>
</tr>
</tbody>
</table>

Let's now use Excel to produce a graph (or chart) of race times. First, open Excel by double-clicking the Excel icon. You will then see a big array of boxes, or cells. These cells are arranged in rows and columns, and the position of any cell is given by its column (specified by a letter) and row (given by a number). The first cell is labeled A1, and is the one in the upper left corner. So the cell that is the third to the right (C) and fourth down (4) is C4.

Position the cursor (which will change from an arrow to a cross) with the mouse until it is right over cell B2. Click the mouse button to select that cell. Enter James's time here by typing "17" and following this with the "enter" key. Now select the cell below this, and enter Mary’s time. Finally, enter Tim’s, Joshua’s, Hannah’s and Robbie's times in the next three cells.
Before you can make a graph of this, you need to tell Excel what to graph. To do this, position the cursor over the first cell (B2). Hold the mouse button down, and drag down to the last cell (B5). Release the mouse button, and all four cells should be selected (the first one looking a bit special—don't worry about that). Now go to the "Insert" menu and select the "Chart" menu item to start a questioning process through the Chart Wizard. You could also start the Wizard by clicking the Chart Wizard icon on the standard toolbar at the top of the screen.

For a quick graph, click on the "Finish" button in the first dialog window that comes up. You should now have a chart of race times. Let's print a copy of this out. In the file menu, select the menu item "Print." A confusing set of questions will appear; just click the "OK" box, and a moment later you should have a nice printout of the graph at the laser printer in the laboratory. Each of you should try writing your own explanation of what this graph is—what do the bars mean? Then talk with your partners and see if you agree. (You can also print by clicking the print icon)

Look back at your bar chart. The numbers underneath the bars are not very useful. The 1, 2, 3, 4, 5, 6 just refer to which entry each bar is associated with. We'd rather have them labeled with the racers' names. To do this, enter the appropriate names in cells A2 through A5. (If your graph covers these cells, you can click and drag on the graph to move it around.) Now select cells A2 through B5, click the Chart Wizard and click the finish button. What happened with the names? Print a copy if you would like.

Notice that if you change the spelling of a name or a number in time column, the graph makes the appropriate changes. The data in the columns are "dynamically linked" to the graph. This is a very nice feature of Excel.

**Entering Multiple Sets of Data**

We might also like to see if there is any correlation between the racers' heights and their times. In cells C2 through C5, enter those heights (given in inches):

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>James</td>
<td>71</td>
</tr>
<tr>
<td>Mary</td>
<td>65</td>
</tr>
<tr>
<td>Tim</td>
<td>69</td>
</tr>
<tr>
<td>Joshua</td>
<td>70</td>
</tr>
<tr>
<td>Hannah</td>
<td>42</td>
</tr>
<tr>
<td>Robbie</td>
<td>34</td>
</tr>
</tbody>
</table>

Now that we have two columns of numbers, we'd better be careful, and label them. In cell B1 (above the times), enter the word "times." In cell C1 (above the heights), enter the word "heights." Things are starting to get more complicated here, so let's save a copy of your worksheet. To do this, choose "Save" from the "File" menu. It will ask for a name for you to type in instead of "Worksheet1." Type in something you can remember, and then click OK. If you are using a Mac in the Physics 131 laboratory, your file will appear as an icon on the Desktop. On other machines, it will probably appear in the Excel folder or subdirectory. Just remember where it is so you can delete it later.
Now, select all of the data (A1 to C5), and make a new chart of that. Do you understand what the bars mean here? Excel helps keep things clear by making use of the labels you put at the top of the columns. You can get rid of this (and also bring it back) by using the Chart Wizard. Click on the graph and then click on the Chart Wizard icon. Move to the Wizard window (by clicking on the next button) that has the legend index tab. Select the tab and you'll see what to do.

You are probably now eager to know a few other things, such as print just the graph without the cells in the background. To do this, single click on the graph, and a thick border around the graph will appear. Now, when you print, you'll only get the graph. This border goes away when you click back on one of the cells in the worksheet. And by now, you must surely have messed up a couple of graphs and would like to clear them away. To get rid of a graph, click once on the graph to select it, then select Clear under the Edit menu. What about changing the size of a graph? Click once on the graph. The little black squares on the graph border are "handles." Click and drag on them to resize the graph.

**Doing Arithmetic Calculations on Sets of Data**

The other real power of a spreadsheet is that it can do complicated arithmetic on all these numbers. Let's say that we wanted to know what speeds these race times corresponded to. Speed is just distance divided by time (in units like miles per hour, or feet per second). Let's say that these times were for a 100 foot race. We are going to put the speeds into the D column, so label D1 "speed." Now, select cell D2. Into that cell, enter the expression

\[
=100/B2
\]

which tells Excel to enter in a number that is equal to 100 divided by whatever number is in cell B2. Once you hit enter, you should get roughly 5.88 in that cell. You could now enter the corresponding formulas into cells D3 through D5, but there is a trick. Click on cell D2, hold the mouse button down and drag down to D5, and then release the button. Look what happens. Select one of the cells to see what formula was entered; Excel was smart and automatically changed B2 into B3, B4, and B5 for the appropriate cells. If you don't see this, make sure to ask one of us about it!

**Making Comparisons Between Sets of Data**

Often, we want to find out if one particular number (say the height) is related to another number (say the speed). So, for this data, we might expect that faster speeds go along with taller heights. To see if this is true, we make an "X-Y" or "Scatter" graph. In this case, we will plot speed (denoted by the vertical position on the graph) against height (given by the horizontal position on the graph). To do this, select the last two columns (C1 through D5). Start the Chart Wizard and then click on the "XY (Scatter)" graph, then click the "Finish" button. Print a copy of this new graph, and make sure you and your partner understand what it means.
You should experiment a bit with Excel now on your own. For example, try making graphs of just made up numbers, or try putting in other types of formulas. You might also want to try to change the speed formula so that the speed is in miles per hour, and not feet per second. Also, you might want to go through all the Chart Wizard windows by clicking "Next" instead of "Finish" as long as you can. Especially important is the last of these windows, where you can add a label to your graph, which will allow you to identify your printout from everyone else's!

**Excel Functions**

Excel has a variety of built-in functions, such as a function for summing and averaging, for fitting a least-squares straight line, or for finding variances and standard deviations. The Function Wizard allows you to explore these functions. You will also find a list of useful functions in the "Useful Excel Functions" document on the Physics 131 Website and in an appendix to your Physics 131 Lab Manual. This list will expand during the year, so please let us know if you have found a useful function that we should add to the list.
APPENDIX B: Useful Excel Functions

Overview

Rather than writing formulae for usual calculations such as summing or averaging, Excel provides a large number of built-in functions for your use. You can see the complete list of functions by clicking on the paste function icon, fx, on the standard toolbar. This icon starts the "paste function" which leads you through the use of a particular function. Specifically, to use the paste function, you should:

- Select the cell that will contain the function
- Type the symbol, =, into the cell so that Excel knows that the following characters will be a function
- Activate the Paste Function by clicking on its icon

Try this for adding two numbers. First, enter two numbers in adjacent cells. Then select the Sum function in paste function list and follow instructions. In this process you'll be asked to select a set of cells for the addition (just highlight the two adjacent cells with your mouse). Look at the formula entered into the cell showing the sum.

Once you know the syntax for a particular function, you need only enter this syntax into the cell designated to contain the function results. There is no need to use the paste function process; you can type =Sum(, then highlight the two cells containing the numbers to sum, then type ) to close the parentheses, then press return and it's done.

You can use these processes for functions that produce a single result such as a sum or an average. However, some functions produce multiple results, an "array" of results. Excel calls these functions "Array functions". I'll describe how to use these as they arise in the following function list.
Function List

- **Sum**: adds all numbers in a range of cells. Examples, =sum(a1,a3,b5), = sum(a1:a10).
- **Average**: returns the arithmetic mean of its arguments
- **Stdev**: estimates the standard deviation of its arguments
- **Cos, Sin, Tan**: trig functions, arguments in radians
- **PI**: returns the value of Pi.
- **ln**: returns the natural log of its argument
- **exp**: returns e raised to the power of a given number
- **Count**: counts the number of cells in a list
- **Max, Min**: Returns the maximum or minimum value in a range of cells.
- **Regression**: Fits a least-squares straight line to a list of x-values and a list of y-values and determines the uncertainties in the values of the slope and the intercept based on the scatter of the data points about the straight line. These uncertainties do not include the uncertainties associated with individual data points.
- **Tools menu --> Data Analysis menu --> regression**
- **With the mouse**: click on Input x-range box and select data on spreadsheet
- **Repeat for Input y-range box**
- **Select output range or just use the default to place the results of the fit on a new worksheet**
- **The output is complicated but the slope and intercept with associated uncertainties are clearly labeled.**
- **Trendline**: Probably the easiest way to fit a straight line to your data is to use the trendline feature under the Chart menu. Just click on trendline and use its menu. If necessary, you can later select the trendline on the graph and use the format menu to change the number of decimal places in the equation printed on the graph (just select “number” and set the number of decimal places).
- **Linest**: Fits a least-squares straight line to a list of x-values and a list of y-values. This is a useful function that is a bit complicated to use since it returns the slope and intercept (m and b in y = mx + b) in addition to the standard errors in the slope and the intercept. To use this function:
  - Select a 2 by 2 square block of cells to hold the results of the linest function.
  - Type =linest(y-value cells, x-value cells,,1). Note the two commas! For example, =linest(b2:b10,a2:a10,,1). Here the y values are stored in b2:b10 and the x values in a2:a10.
  - Hold down the Shift and CTRL keys and press Enter
  - The first row shows the slope and the intercept
  - The second row shows the standard errors in the slope and intercept.

You can now use the slope and intercept to create an additional column next to your measured y values. You can then create a graph containing both the measured and fit y-values.
APPENDIX C: Logger Pro Graphing/Printing

With a shared printer, there is always some confusion as to whose graph is being printed and what order do they print? One solution is to label each graph. Then when it comes out of the printer, it is easy to identify the owner.

TO LABEL YOUR Logger Pro GRAPH:

- Under File menu at top
- Choose “printing options”
- Give your graph a name
- The title won’t show up on the screen, but will be printed on the graph