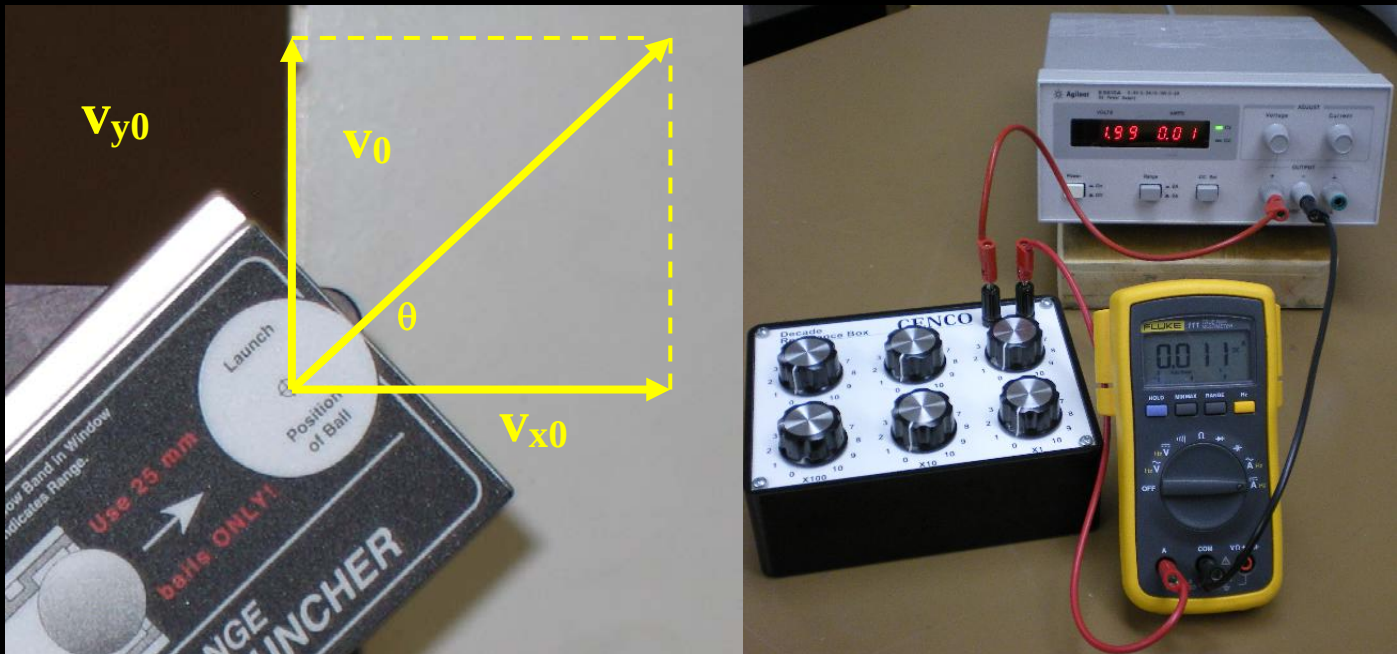


Laboratory Manual

For Basic Physics

PHYS:1400



John A. Goree, Chuck Williamson, and Anthony Moeller

This electronic version of the manual is for the fall semester of 2017.

Department of Physics and Astronomy
The University of Iowa
Iowa City, Iowa

Acknowledgements

This manual is intended for a one-semester survey course for physics, PHYS:1400, Basic Physics.

Many of the experiments used in this course were originally designed for more advanced courses. The original authors of these experiments were John Goree and Chuck Williamson. In recent years many of these experiments have been adapted into experiments more appropriate for this course. Several of the previously existing experiments (also written by Goree and Williamson) also underwent significant revision. These adaptations and revisions were made by laboratory coordinator Anthony Moeller with feedback from TAs and lab setup crew members. Additionally, this manual is now available to you in full color, which should improve the usefulness of many pictures and diagrams.

May, 2017

Laboratory Guidelines

You have many things to gain from your laboratory experience:

- A better understanding of basic physics concepts
- Practice conducting systematic and rigorous scientific research
- Developing problem solving skills
- Developing familiarity with laboratory instruments and computer software interfaces.

Regarding attendance: Your course instructor will inform you of his or her expectations for laboratory attendance. You should try to participate in every experiment. This course has been structured so that new experiments tend to build on concepts and experience gained from previous experiments.

Preparing for Lab:

The most valuable resource you have in lab (aside from your brain) is time. You have a limited amount of time to perform each experiment; you do not want to waste time fumbling around wondering what to do next. Here is what you can do to properly prepare for lab:

1. **Read the manual.** The manual for each experiment has four parts:
 - i. *Introductory Material*, which describes the physics you will be studying.
 - ii. *Pre-Laboratory Questions*, which are to be done at home, before lab.
 - iii. *Experimental Procedure*, with instructions you will follow while in lab.
 - iv. *Analysis Questions*, which are to be answered in your Lab Report.
2. **Do the Pre-Laboratory Questions.** The Pre-Lab Questions are designed to start you thinking about the concepts you will explore during the experiment. Teaching Assistants will collect the Pre-Lab Questions at the beginning of lab, and their completion will account for 10% of your lab grade.

Suggestion: if you also write your result in your lab manual, you will be able to refer to it while doing the lab.
3. **Consult your references.** If there are parts of the manual you do not understand or you have difficulty with the Pre-Lab Questions, then look in your physics textbook, talk with the TA or the professor.

What to Bring to Lab:

1. A sharp pencil and an eraser. Write your lab reports in **pencil** so that you can erase your mistakes.
2. A calculator.
3. The **entire** lab manual, including previous experiments and the Glossary. You will often need to do a procedure that was described in detail earlier.
4. ID cards will occasionally be needed to check out equipment – make sure to bring yours!

What You Will Hand In:

1. Answers to the Pre-Laboratory Questions. Hand these in at the **beginning** of the lab session.
2. The Laboratory Report, as described below.

Writing the Laboratory Report:

A complete Laboratory Report consists of the following five parts:

1. The title of the experiment, the date, your name, the name of your lab partner(s), the name of the TA, and the section number.
2. **Raw Data.** Data must be neat and legible, and should be presented in a table when appropriate. Data must have labels and units. You should indicate the uncertainty involved in acquiring the data. For example:

Mass of gold air track glider: 153 ± 1 g

Many of the experiments include worksheets to guide you through the collection and presentation of your data. If there is no worksheet for a particular experiment, then be sure to include a brief explanation of what you are doing at each step in the procedure so that the context of your data is clear.

3. **Sample Calculations.** In every experiment you will use your raw data to make various types of calculation. You must therefore demonstrate to the TA that you understand how the calculations are performed by writing out sample calculations whenever the Experimental Procedure asks you to show your work in a **SAMPLE**

Part II: Characterize the Launcher

Calculate the theoretical range of the projectile using Eq. (3.19):

$$x_T = \frac{v_0^2}{g} \sin(2\theta) = \frac{(4.1 \text{ m/s})^2}{9.81 \text{ m/s}^2} \sin(2 \times 37^\circ)$$

$$x_T = \left(1.71 \frac{\text{m}^2}{\text{s}^2} \frac{\text{s}^2}{\text{m}} \right) \sin(74^\circ)$$

$$x_T = (1.71 \text{ m})(0.961)$$

$$x_T = 1.6 \text{ m}$$

CALCULATION. (A list of the required sample calculations is included at the end of each Experimental Procedure.) Use a separate piece of paper and clearly state what you are calculating, what part of the experiment the calculation is for, and the equation you are using. Write out the calculation step-by-step and include units to avoid making gross dimensional errors. If you need to solve an equation for a variable, always do the algebraic manipulation first, and then plug the numbers in at the end. An example of a sample calculation is shown above.

4. **Graphs.** Any graphs or images you print during the experiment must be a part of the Laboratory Report.
5. **Analysis Questions.** Most experiments have a few Analysis Questions posed at the end that are to be answered once the laboratory work is complete.

Laboratory Report Grades:

Laboratory Reports will be graded by your TA according to a 100-point scale, as shown in the worksheets. It is typically like this:

10 pts.	Pre-Laboratory assignment (collected at the beginning of lab).
30 pts.	All experimental data, including any graphs and figures.
10 pts.	Correct units and number of significant figures for all numerical data. Uncertainty values on measured data.
20 pts.	Sample calculations.
20 pts.	Analysis Questions.
10 pts.	A clean laboratory bench at the end of class. This must be verified by the TA. To get full credit, you should ask the TA to inspect your bench and initial your Laboratory Report before you leave.
100 pts.	TOTAL POSSIBLE POINTS FOR EACH LAB REPORT

Laboratory Safety:

The potential health hazards in this laboratory course are relatively few, but please use common sense, and pay heed to the safety warning boxes in this manual. Respect your colleagues: they will be concentrating on their own experiment and may not be aware of what you are doing. Respect and take good care of the equipment: other students will use it after you. Safety glasses are required for certain experiments and will be provided for you.

Table Of Contents

Most experiments are divided into several parts. Professors may choose to omit some parts if the material has not been covered in lecture. The TA will tell you at the beginning of a lab session if a particular part is to be omitted.

The experiments in this manual, and the worksheets, appear in the order listed in the table below.

A1	Precision Measurement
A3	Acceleration of Gravity
A5	Projectile Motion
A4	Hooke's Law and Simple Harmonic Oscillators
A6	Conversion and Conservation of Energy
A8	Specific Heat
A9	Charge Measurement
A11	Ohm's Law And Series/Parallel Circuits
A12	Speed of Sound
A16	Geiger Counters and Radioactive Shielding
A13	Thin Lenses

Glossary Of Laboratory Instruments

Accelerometer

This instrument is actually three accelerometers in one. The three accelerometers are positioned on orthogonal x -, y -, and z -axes, and the orientations of the axes are indicated on the device's label. (The circle and dot symbol by the z -axis means that the z -axis points straight up out of the top of the accelerometer.) When the 3-axis accelerometer is moved in some arbitrary direction, the corresponding acceleration vector $\mathbf{a}$ is measured in terms of its three component vectors $\mathbf{a}_x$, $\mathbf{a}_y$, and $\mathbf{a}_z$ along the instrument's x -, y -, and z -axes. Each axis has its own output plug, so the LabPro is sent the magnitude and sign of each component of $\mathbf{a}$.

The accelerometer's three sensors are very tiny springs mounted inside computer chips. Because the sensors are springs, the instrument responds to the acceleration of gravity when the device is stationary. To understand this, think about holding a string up by its ends: the string droops down in the direction of gravity. If the two ends of the string are released simultaneously, then the string flattens during free fall. The same principle applies to the accelerometer. Gravity displaces the sensor springs relative to the housing when the housing is stationary, and the total magnitude of the output signal:



$$|\mathbf{a}| = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (\text{G.1})$$

is equal to 9.8 m/s^2 . If the accelerometer is dropped, then the housing and the springs fall together. The springs return to their equilibrium position relative to the housing, so the output signal is 0 m/s^2 .

The Logger Pro software must have calibration data in order to correlate the accelerometer's output signals with values of acceleration. To calibrate the accelerometer, you will provide Logger Pro with two data points using the earth's gravity as a reference. The procedure for calibrating the y -axis of the accelerometer can be found in the Computer Use Glossary.

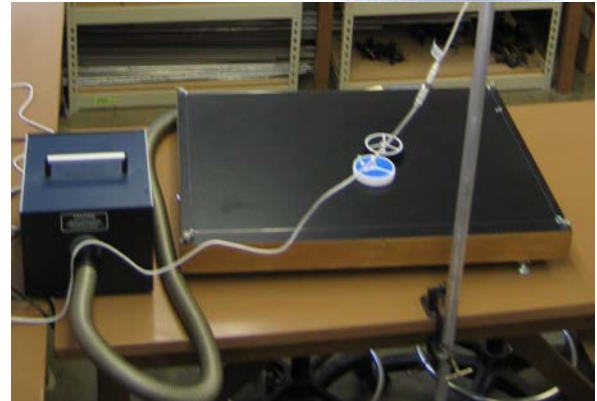
Air Blower

This is the air source for both the air track and the air table. The blower's output tube connects either onto the end of the air track or onto the side of the air table.



Air Table

This device is similar to an air hockey table. A blower sends air into the table, and the air comes out through an array of tiny holes drilled in the top surface of the table. The force of the emitted air is strong enough to support small objects with smooth, flat bases, such as pucks. Static and kinetic frictional forces are very small for floating pucks and have a negligible effect on the puck's motion as they move across the table. A wire border keeps the pucks on the table.

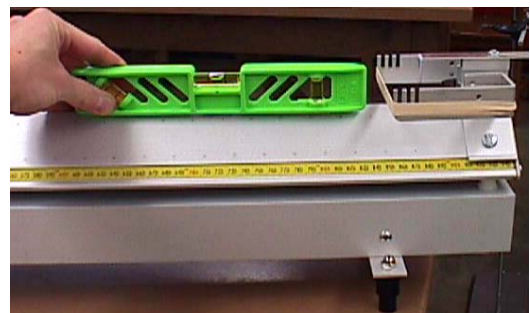
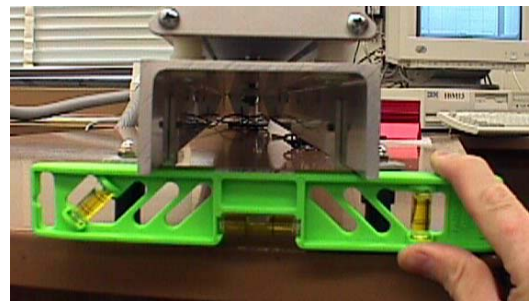
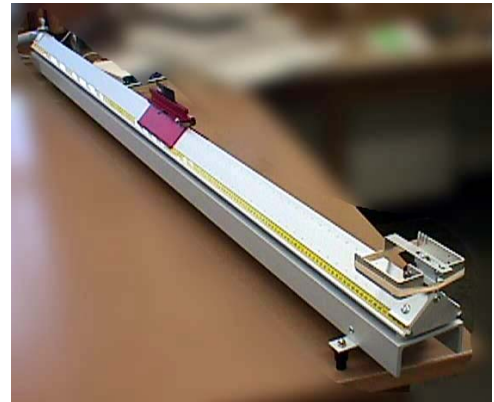


Air Track

The air track is a one-dimensional version of the air table. The cross section of the air track is triangular, pointing up. Air is blown into the track at one end and comes out through hundreds of tiny holes on the top two surfaces of the triangle. A glider moves along the track by floating on a cushion of air; there is no direct physical contact between the glider and the track, so there is very little friction. This feature makes the air track an excellent tool for studying kinematics. A free-moving glider will eventually slow down due to air drag and due to the energy loss that occurs when the glider makes inelastic collisions with the springs at either end of the track.

The air track is two meters long and has a ruler mounted on one face. The air track must be level for the glider to float properly. Use the following procedure to level the air track:

- Check the side-to-side tilt of the air track by placing a level underneath on the end as shown. Adjust one of the air track's two black feet until the bubble in the level is



centered. The *bottom half* of each black foot can be twisted while holding the top half. The feet raise the track when twisted clockwise and lower the track when twisted counterclockwise.

- Check the end-to-end tilt with the level at several points along the track. Fine-tune this test by turning on the air blower and placing the glider on the track. The glider should not accelerate rapidly, but it may drift about lazily. If the track is tilted, adjust it using the two black feet. Check the side-to-side tilt again, too. This process may require several iterations.

Air Track Gliders

These Y-shaped pieces of metal nestle down snugly on the air track and are forced to float when the blower is turned on. Spring bumpers can be attached to either end of the gliders, flags (for tripping photogates) can be inserted into the top slot, and weights can be added on to side-mounted screws. Please be very careful with the gliders, and set them on Styrofoam sheets when they are not being used. Dropping a glider or scratching the underside of its wings can ruin the glider.



Aneroid Calorimeter

The aneroid calorimeter is a device designed for the study of heat and heat transfer. The calorimeter consists of an aluminum cylinder encased in a foam-insulated housing, and it approximates what is known in thermodynamics as an isolated system, a system that does not exchange either mass or energy with its surroundings. The cylinder has two holes drilled into it, one for a sample material and one for a thermometer (so that the internal temperature of the calorimeter can be monitored).



Computer

Each lab station comes equipped with a laptop computer with a Windows operating system (Windows version may vary). Many of the measurements you make during this

laboratory course will be done with the help of the computer. Computers are useful in lab because: (a) they can record data points faster than humans; (b) they can do long, tedious mathematical operations without error (or grumbling); (c) they can make pretty graphs; and (d) they can assist in the analysis of video images.

A very important point must be made about the human/computer partnership in laboratory work:

YOU MAKE THE MEASUREMENTS

THE COMPUTER DOES NOT MAKE THE MEASUREMENTS

All that the computer “knows” about the experiment is what you tell it. If you have made a calibration error or some other type of mistake while setting up the Logger Pro software, then the numbers that the computer spits out probably will be pure garbage. You have the responsibility of evaluating the computer’s data to see whether or not the data makes sense.

Digital Camera

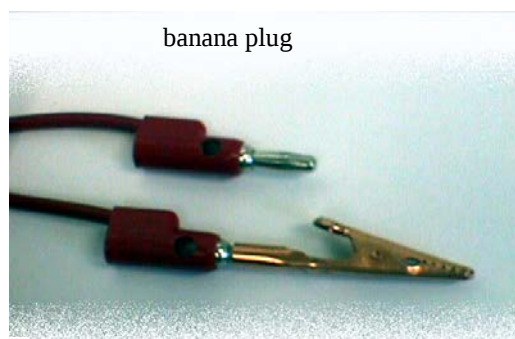
Movies and videos record a series of still images (or frames) rapidly replaced one after the other. The human brain lingers on an image for about $1/15^{\text{th}}$ of a second, so the illusion of motion can be achieved by making the frame rate faster than 15 Hz. Feature films use 24 frames per second*, while television and digital video use 30 frames per second.



You will make physics movies in several experiments using a digital camera (which may or may not look like the one shown here) at 30 frames per second. You will have to aim the camera towards where the action takes place. You will use Tracker software to analyze the physics in your movie.

Electrical Connectors

A banana plug is a connector that fits into a variety of other connectors, including binding posts, alligator clips, and input connectors on multimeters. An alligator clip is a something like a clothespin: it can be made to connect to anything that its jaws can hold.



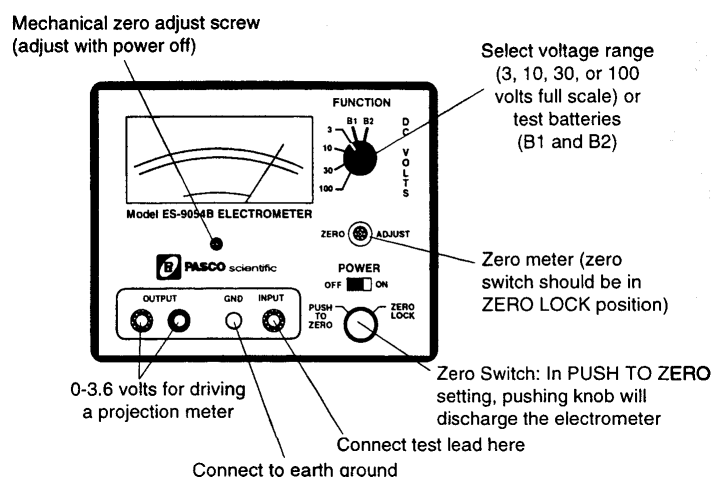
banana plug

alligator clip

* Old movies used a slower frame rate of 20 fps. You have probably seen a silent movie in which the action is especially comical because everyone is scurrying around more quickly than in real life. This happens because the broadcaster shows the movie at the wrong speed, 24 fps instead of 20 fps. More frames are shown per second than when the movie was filmed, so the action speeds up by about 20%.

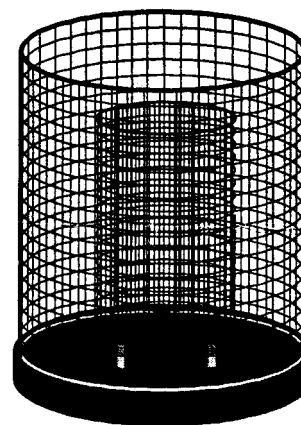
Electrometer

An electrometer is a kind of voltmeter. Compared to typical voltmeters, it has a particularly high input impedance of $10^{14} \Omega$, which means that this instrument's high input impedance allows a measurement without disturbing the charge of the object that you measure.



Faraday Ice Pail

A charge placed inside a conducting surface induces an equal charge on the outside of that surface. The Faraday ice pail is a set of two concentric metal screen cages. When you put a charged object inside the inner cage, an electric potential V appears across the two cages. You can measure this potential with an electrometer.



Faraday ice pail

Force Sensor

The dual range force sensor can measure the magnitude of stretching and pulling forces. The sensitivity range may be set to either $\pm 10 \text{ N}$ or $\pm 50 \text{ N}$ using a switch on the instrument's front face. The active sensor component on the instrument is a gray metal block with a tapped hole. A bumper and an eye-hook are provided that both screw into this hole.

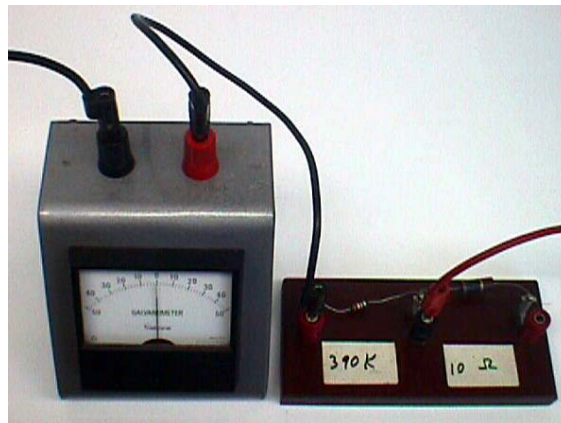
When the metal block is pushed or pulled, strain is generated in a metal bar mounted on the inside of the force sensor. This strain induces a voltage in the instrument's electronics; the amount of voltage is linearly proportional to the magnitude of the applied force.



The *Logger Pro* software must have calibration data in order to correlate the force sensor's output signal with values of force. To calibrate the force sensor, you will provide *Logger Pro* with two data points using a known mass as a reference. The procedure can be found in the Computer Use Glossary.

Galvanometer

A galvanometer is a mechanical meter that measures current. It is often used in series with a resistor, as shown here, to limit the current.



“Ideal” Spring

In your physics textbook, an ideal spring is described as a spring that has no mass and has a perfectly linear relationship between an applied force and the distance the spring is stretched, $F = kx$. Real springs do have mass, however, and gravitational effects cause a spring to stretch a little when held vertically even though no extra mass is attached to the bottom of the spring. Furthermore, the top coils of the spring are stretched further apart than the bottom coils because the top coils are pulled by almost the entire weight of the spring while the bottom coils feel the gravitational force of only a small part of the spring. This can introduce some non-linearity into the spring's response when a mass is attached.

The “ideal” spring shown in the picture at the right has a built-in correction to this problem. The spring is tapered – the coils at the top of the spring have a smaller diameter and are more tightly wound than the coils at the bottom of the spring. With this design, the spacing between coils remains the same even when the spring is hung vertically, and the spring behaves very linearly.

Inclinometer

The inclinometer (or angle finder) allows us to quickly and easily find the angle of a given incline. Simply turn the inclinometer on using the ON/OFF button and set the device on the slope with the long portion of the inclinometer aligned with the slope. The inclinometer will quickly give a reading of the slope in degrees.



Logger Pro Software

Logger *Pro* is the program you will run on the computer to “talk” with the LabPro device. In order for Logger *Pro* to make sense of the voltage values sent to the computer from the LabPro device, you must tell Logger *Pro* what sensors are connected to what input jacks, and how the sensors are to be used. Logger *Pro* processes the voltage values for you and displays the results in tables and graphs. The program has a number of sophisticated data analysis tools that you will learn how to use gradually throughout the laboratory portion of this course.

Mechanical Equivalent of Heat Apparatus

The Mechanical Equivalent of Heat Apparatus consists of a cylindrical aluminum calorimeter that can be rotated with a crank handle. A frictional torque is applied to the calorimeter by hooking a mass to a nylon rope and wrapping the rope several times around the calorimeter. The heat generated from the friction between the rotating calorimeter and the nylon rope raises the temperature of the calorimeter. The total number of turns N is recorded by a mechanical counter that advances with each turn of the crank handle. An infrared thermometer is mounted near the aluminum calorimeter component of the Mechanical Equivalent of Heat Apparatus (MEHA).



Microphone

Sound travels through a medium as a longitudinal fluctuation in the medium’s density or pressure. For example, air at the earth’s surface has a pressure of 1 atm. When air is a medium for a sound wave, the air pressure varies slightly above and below 1 atm of pressure as the sound wave passes through. The microphone converts the physical fluctuations of air pressure into a voltage signal. You will use an oscilloscope to record this voltage, allowing you to characterize the sound. These microphones are battery powered; do not forget to turn them off when you are done.



Motion Detector

The motion detector is useful for determining the position of an object to within a few millimeters. (With careful calibration, the precision can be improved to less than a millimeter.) The motion detector emits an ultrasonic pulse, starts an internal stopwatch, and listens for an ultrasonic echo. If an echo comes back, the device can calculate the position of the reflecting object according to:

$$x = \frac{v_s \Delta t}{2} \quad (\text{G.4})$$

where Δt is the elapsed time between the emitted pulse and the echo, and v_s is the speed of sound. The factor of one-half is included because the ultrasonic pulse must travel to the reflecting object and then back to the motion detector.

The ultrasonic pulse is emitted in the shape of a cone with a half-angle of 15° . Since the motion detector relies on a reflected signal, the presence of other objects within the cone (like your arm) can interfere with the measurement. The $x(t)$ signal will be noisy in this case, with lots of spikes. There is a minimum range for the motion detector which varies depending on the model. The green motion detectors have a significantly lower minimum range than the blue motion detectors.



Multimeter

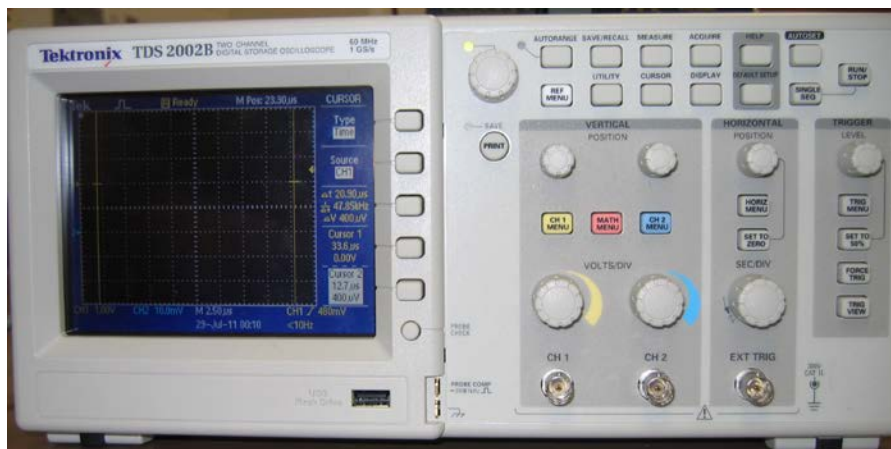
Multimeters can measure three different electrical properties: voltage (in volts, V), resistance (in ohms, Ω), and current (in amps, A). Only one property can be measured at a time, and the choice is set by adjusting the position of a large dial on the face of the multimeter.

Typically the multimeter's display is limited to four significant digits. Since voltage, resistance, or current can span many decades (orders of magnitude), the front dial is used to choose a display range appropriate to the experiment. The dial position may be changed at any time.



Oscilloscope, Digital

You will use the oscilloscope in the “W Series” labs to look at sound waves. The trace that you see on the scope will show voltage on the y-axis and time on the x-axis. You will be able to adjust the voltage and time settings on the scope to better analyze your signal. More details will be given in the Experimental Procedure section of the relevant experiment.



Photogates

The photogates you will use in this experiment are U-shaped, and have a small light source on one arm of the U and a light detector directly opposite on the other arm of the U. The photogate sends one voltage to the LabPro device when the light from the source reaches the detector, and sends a different voltage when the path is blocked and no light reaches the detector.

The photogate's light source emits an infrared wavelength that is not visible to the human eye. The photogate's detector is sensitive enough to distinguish the infrared wavelength from the visible spectrum, so the room lights do not have to be turned off when you use the photogate.

Another name for a photogate is an electric eye. Photogates are often a key component in burglar alarm systems.



Projectile Launcher

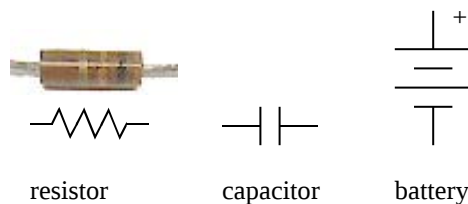
This spring-based ball launcher is used for studying projectile motion. The launcher shoots a bright yellow ball, about 2.5-cm in diameter. The launcher is cocked by pushing the ball into the barrel with the ramrod until the barrel latches. There are three latch points, corresponding to short, medium, and long range launches. You should only use the short-range setting, which will propel the ball about one meter. Pull up on the yellow string to launch the ball. (If you must see how far the launcher can shoot on the long-range setting, then ask the TA to demonstrate it for you.) To obtain the best experimental results (i.e., the most reproducible), the launcher should be clamped to the lab bench.

The launch angle is changed by loosening a screw on the back of the launcher mount and then rotating the barrel about its pivot point. The pivot point is located at the mouth of the launcher, so changing the launch angle does not change the height from which the ball is launched. A small plumb bob hangs in front of degree markings on the rear of the launcher to simplify measurement of the launch angle.



Schematic symbols

A resistor is an electronic component that obey's Ohm's law. It has a resistance, measured in Ohms, and a tolerance, i.e., precision. In schematic diagrams, it is shown as a zig-zag line. A capacitor is shown as a pair of parallel lines, as a metaphor for a pair of parallel plates. A battery is a stack of short and long parallel lines, as a metaphor for electrode plates.



schematic symbols

Spectrometer

The spectrometer is used to measure the deflection angle of a ray of light passing through either a prism or a diffraction grating. The spectrometer has a collimator that allows the user to adjust the width of the slit for incoming light, and a rotating, adjustable telescope to allow the user to view the deflected light at varying angles.

Wear UV goggles when viewing light sources through the spectrometer, as many of the sources used in these experiments give off UV light than can damage your eyes.



Temperature Probe, Direct Connect

This temperature probe connects directly into the LabPro. It allows you to record temperatures directly to Logger Pro applications.



Thermometer, Electronic

This instrument is a sophisticated type of thermocouple. One junction point is located at the end of the probe tip. The second junction point (the reference) is inside the instrument and electronically calibrated. The user can select either the Celsius or Fahrenheit scale. The thermometer has an operating range of -50°C to 1300°C and is accurate to 0.3%.



Thermometer, Digital Infrared

You will use a digital infrared thermometer to measure the temperature of the aluminum calorimeter in the mechanical equivalent of heat lab. The advantage of this thermometer is that it does not have to touch the surface whose temperature is being recorded.



Tracker Software

Tracker allows you to analyze the motion of objects in a digital movie loaded onto the computer. You establish an x,y -coordinate system for the movie, and then take data by clicking on the position of objects frame by frame. Tracker defines the position coordinates x and y in terms of image pixels. However, the program also allows you to identify the length of an object in the movie (such as a meter stick), in order to create a scaling factor: the number of pixels per meter. The position of an object in the movie is then reported in terms of meters.



Vernier LabPro Data Collection Interface

The LabPro device is the intermediary between the computer and all the electronic sensors and probes you will use. The LabPro device provides power to these sensors and receives back electrical signals that correspond to physical properties.

Humans make most of their physical measurements using their eyes, by comparing distances. Rulers, flow meters, mass balances, and thermometers all have graduated distance scales that our brain uses to decide “This distance is 1 unit, and this distance is 2 units, etc.” With electronic sensors, however, humans measure physical properties using a scale defined by electrical voltage. Through calibration techniques, the computer is told that “This level of voltage is proportional to 1 unit, and this level of voltage is proportional to 2 units, etc.” When LabPro sends a voltage value for some physical

property to the computer, the computer converts the voltage to a number using the pre-set calibration scale. You then read the number off of the computer screen.

The LabPro has six input jacks for connecting with sensors, a single cable connection on the side for connecting with the computer, and an input for power. There are two different types of input jacks: analog and digital. Analog sensors use the jacks marked CH1 through CH 4, and the digital sensors use the DIG/SONIC 1 and DIG/SONIC 2 ports. Different sensors use different plugs – you will be unable to insert a digital jack into an analog receptacle and vice versa.



Computer Use Glossary

USING LOGGER PRO SOFTWARE

Prepare the Computer Interface:

- Make sure the Vernier LabPro device is plugged in. The green diode on the top should be lit.
- Start *Logger Pro*. *Logger Pro* will begin running. (If a box appears stating “Connect to LabPro”, then either the LabPro interface is not plugged in or is not connected to the computer. Ask the TA for assistance.)
- The *Logger Pro* screen should look similar to the Photo. You need to prepare *Logger Pro* for a photogate experiment by opening an Experiment File.

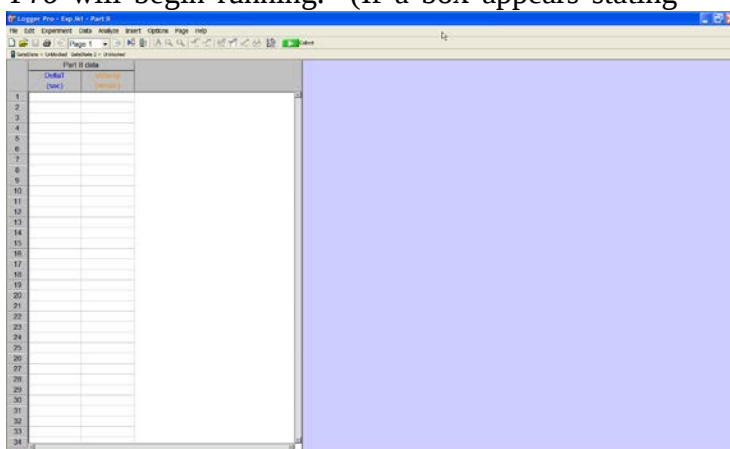


Photo . Screenshot of *Logger Pro*

To do this, select “File→Open...” (or use the  button) from the pull-down menus, and then select the file that is given in your lab instructions.

Words of warning ...

Use some common sense to get good results: It is obvious to you when a trial begins and when the trial is over. The computer, however, is unaware, which can lead to gross errors in your data if you are not careful.

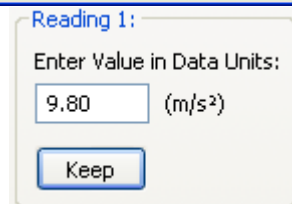
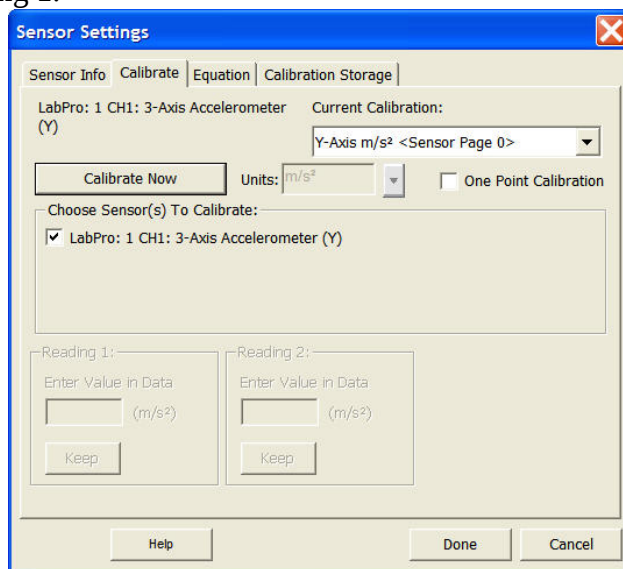
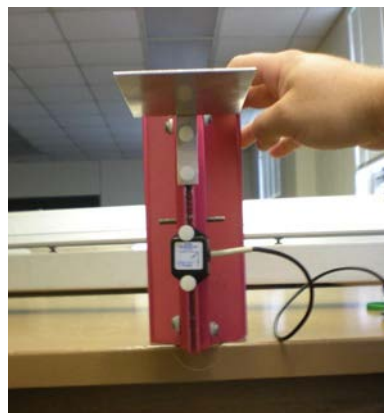
MAKE SURE THAT THE VALUES GIVEN BY THE COMPUTER MAKE SENSE. DO NOT BE AFRAID TO REDO A TRIAL TO DOUBLE CHECK YOUR RESULTS!

Calibrating Sensors:

In order to get accurate results, some sensors must be calibrated. The following instructions outline how each of the sensors that need calibration should be calibrated. Make sure the sensor is plugged into the LabPro device before starting.

Accelerometer:

- Make sure the accelerometer is level, with the axis you are calibrating pointing down to the ground.
- Click on the  button, located in the upper left hand corner of the window. Click on the picture of the accelerometer and select “Calibrate...” from the pop up menu.
- Click on  and enter a calibration value of 9.80 for Reading 1.
- Rotate the accelerometer 180° and enter the value of -9.80 for Reading 2.
- Click  and  to close the sensor window.



Once the accelerometer has been calibrated, the zero position can be redefined with *Logger Pro*. The accelerometer's signal can be specified as 0 m/s^2 when the accelerometer is stationary, even though the internal sensor springs are displaced.

Accelerometers have many real-world applications; one common use is determining when to release air bags in cars.

Force Probe:

- The eye-hook should be screwed into the force sensor. Mount the force sensor on a post with the hook hanging straight down.

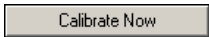
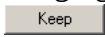
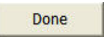
- If the force sensor's range is set to ± 10 N, use a 200-g hanging mass. If the force sensor's range is set to ± 50 N, use a 1-kg mass instead. Calculate the force F of gravity acting on the mass according to:

$$F = mg \quad (\text{G.4})$$

where $g = 9.80 \text{ m/s}^2$. The unit of force is the Newton:

$$1 \text{ N} = 1 \frac{\text{kg m}}{\text{s}^2} \quad (\text{G.5})$$



- Click the  button to set up the force probe. Click on the picture of the probe and select "Calibrate..." from the pop up window.
- Click on the  button. Define the force acting on the sensor as 0.00 N since nothing is hanging from the eye-hook. Enter this value in the window and click on the  button.
- You will now need to enter the second calibration point. Hang the 200 g or 1-kg mass from the hook (depending on your setting). Enter the value of the gravitational force that you calculated for this mass, and then click on the  button. The force sensor is now calibrated and will report positive values of force when the sensor is pulled. Click on the  button, and then the  button to leave the "Sensors" box.

Reading 1:

Enter Value:

1.96 (N)

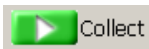
Channel Input: (volts)

2.42



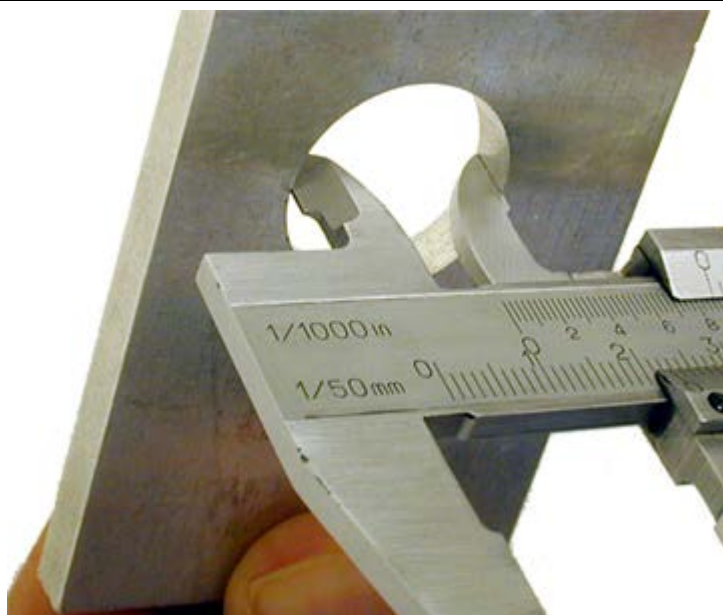
Collecting Data



- The Logger *Pro* menu buttons looks like the bar above.
- Click the  button. This tells Logger *Pro* to start accepting data from the LabPro device. After a few seconds the  button will change to a  button and the computer will be collecting data.
- When you are done collecting data for the experiment, click on the  button. Logger *Pro* will now stop accepting data. This should be done at the end of an experiment before you begin any other trials, unless Logger *Pro* has stopped the data collecting itself (if there isn't a  button, Logger *Pro* has stopped itself).

EXPERIMENT A1:

Precision Measurement



Objectives:

- To determine the density of copper and aluminum.
- To learn to use some common instruments for measuring length and mass.
- To practice making calculations involving experimental errors.
- To learn to plot data and fit it to a straight line.

Introductory Material

In this first experiment:

- You will be introduced to the basic concepts of measurement.
- You will use various laboratory instruments to make measurements of physical properties such as distance and mass.

You will evaluate the uncertainty in your measurements.

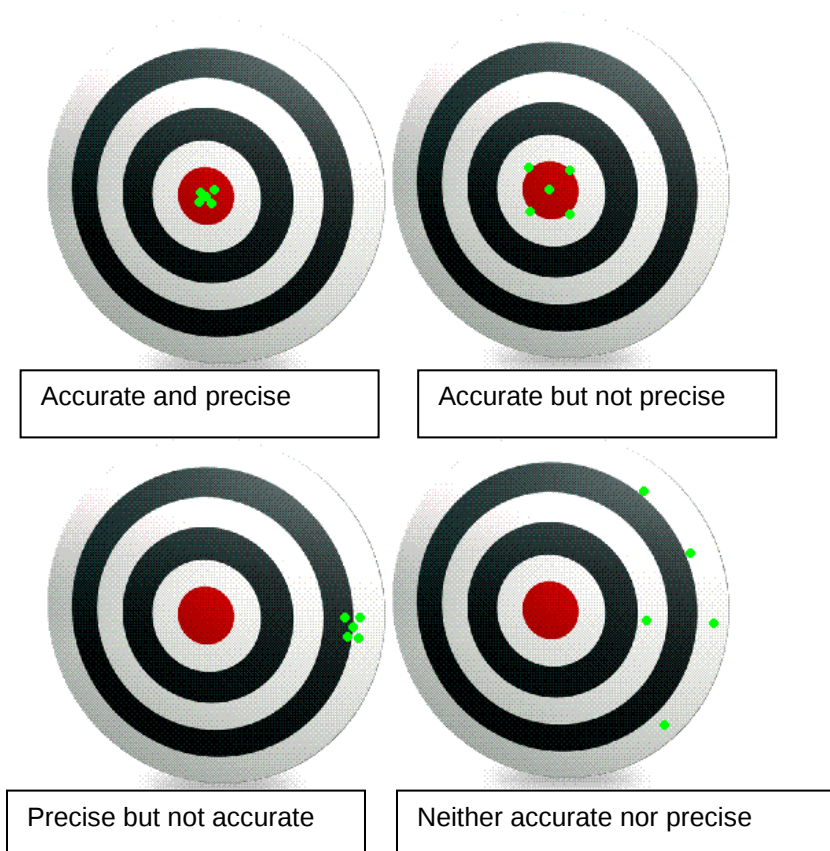
Terminology: Errors, Accuracy, and Precision

In the statistical treatment of experimental data, the word “error” does not mean a blunder or mistake. It means an “uncertainty” in a measurement.

There are two kinds of errors in a measurement:

- **Systematic errors** are errors due to the instrument or technique of measurement. For example if a thermometer is improperly calibrated, it has a systematic error. Sometimes you can detect and measure systematic errors, but sometimes not.
- **Random errors** are produced by a variety of causes, including judgment by the observer in reading tenths of the smallest scale division, or fluctuations in temperature or vibration of the equipment. Random errors often obey a simple statistical distribution.

To illustrate the difference, suppose that you are shooting a target. Not every shot will hit the exact center of the target:



The terms accuracy and precision are widely used as follows:

- **High accuracy** = small *systematic* errors
- **High precision** = small *random* errors

Professional experimental physicists try to report data that are both accurate and precise. A good example of a highly accurate and precise experimental value is the ratio of the mass of the proton to the mass of the electron: $m_p/m_e = 1836.15270 \pm 0.00004$ (that's nine significant figures!).

Significant figures should reflect the precision of your measurement

RULES FOR COUNTING SIGNIFICANT FIGURES	EXAMPLES
The leftmost non-zero digit is the MOST significant digit.	7 50 6 000. 0.004 6 80120
If there is no decimal point, the rightmost nonzero digit is the LEAST significant digit.	7 50 6 000. 0.004680120
If there is a decimal point, the rightmost digit is the LEAST significant digit, even if it is a zero.	750 6000. 0.00468012 0
All digits between the least and most significant digits are counted as significant digits.	7 50 (2 Sig. Figs.) 6000. (4 Sig. Figs.) 0.004 680120 (7 Sig. Figs.)

When you present the result of a measurement in your Lab Report, the number of significant figures you write indicates the precision of your measurement.

Often you will use the results of your measurements in an equation to calculate some other value. This calculated value must also be reported with the proper number of significant figures in order to tell the reader the precision of the value.

A common mistake made by students is to write down a result with too many significant figures. Just because your calculator can display 8 or 10 digits doesn't mean that all those figures are meaningful.

Exp. A1: Precision Measurement

There is a well-defined procedure for determining how many significant figures a calculated number should have. To follow the procedure, you must first count the number of significant figures in your measured values, and you must know the position of the least significant digit relative to the decimal point. The rules for counting significant figures are listed next.

For addition or subtraction calculations, the number of significant figures in the result is determined by *the position of the least significant digit*. If you add numbers with decimals, identify the input number with the fewest number of digits to the right of the decimal; your final answer should have the same number of digits after the decimal.

For multiplication and division calculations, the number of significant figures in the result is determined by *the factor having the smallest number of significant figures*. This is much like the rule for addition and subtraction.

Example 1. Significant figures for multiplication and division.

$$\begin{aligned} 3.52 * 0.106 &= 0.37312 \Rightarrow 0.373 \quad (3 \text{ Sig. Figs.}) \\ 1.445280 / 0.00008 &= 18066 \Rightarrow 20000 \quad (1 \text{ Sig. Fig.}) \\ 140 * 8.961 &= 1254.54 \Rightarrow 1200 \quad (2 \text{ Sig. Figs.}) \end{aligned}$$

Constants and exact numbers in multiplication or division equations, such as the “2” and the “ π ” in “ $2\pi h$ ”, do not affect the number of significant figures in the final result.

Corrections for significant figures should not be made every step of the way in the middle of a long calculation. Rounding can lead to large errors that magnify as inaccuracy in your final result.

Example 2. Rounding too soon can lead to large errors.

Suppose you are calculating the value of the formula $a * b / d$ where $a = 3.11$, $b = 0.66$, and $d = 3.44$. If you wait until the end of the calculation to account for significant figures you get:

$$3.11 * 0.66 / 3.44 = 0.59669 \Rightarrow 0.60 \quad (2 \text{ Sig. Figs.})$$

But if significant figures are rounded each step of the way, then the result is less accurate:

$$\begin{aligned} 3.11 * 0.66 &= 2.0526 \Rightarrow 2.0 \quad (2 \text{ Sig. Figs.}) \\ \text{then: } 2.0 / 3.44 &= 0.58140 \Rightarrow 0.58 \quad (2 \text{ Sig. Figs.}) \end{aligned}$$

In this example, the final value calculated when rounding in each step differs from the correct value by 3%.

$\pm$ *the uncertainty of a measurement*

One of the most important things to learn about measurements is that the value you measure is only part the result. The other part is the uncertainty in that value.

Example 3. The uncertainty is part of your answer.

If you measure the length of an object using a meter stick, and you find that it is 11.3 cm long, you've only found part of the answer. The other part is the measurement uncertainty, which might be ± 0.1 cm. Your final answer is 11.3 ± 0.1 cm. Note that the least significant figure in both the value and the uncertainty are at the same position, relative to the decimal point.

The $\pm$ symbol indicates your error, or uncertainty. If you are asked "What is the precision of your measurement," what that means is "What is the $\pm$ uncertainty of your measurement."

In this course, your TA or instructor will tell you which measurements require you to record your measurement errors. You won't record error values for all your measurements in this course, because it would take too much time. This is a compromise we must make in teaching the course: we would like to show you how experimental physics is really done, but we must also avoid using too much time on tedious calculations so that we can learn physics ideas as well.

Plotting Graphs and Analyzing Linear Data

A well-drawn graph can:

- yield more insight into the relationships between physical properties than a table of the same data.
- allow comparison of experiment and theory.

In this course you will make several graphs, and sometimes you will fit the data for a function. Sometimes you will fit data to a straight line:

$$y = mx + b \quad (1.1)$$

Here m is the slope of the line and b is the intercept on the y -axis. You can do this either by hand, or by using software such as "Logger Pro."

Usually you will perform the fit using software, but if you wish to find the slope and intercept by hand, use the following procedure:

First, draw the best-fit straight line through your data points. Next, choose two points (x_1, y_1) and (x_2, y_2) along the line you have drawn. The most accurate results are obtained when x_1 and x_2 are as far apart as the graph paper will allow. The slope m is:

$$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta y}{\Delta x} \quad (1.2)$$

which has the following units:

$$\text{Units of } m = \frac{\text{Units of } y}{\text{Units of } x} \quad (1.3)$$

Finally, substitute the slope you just found into Eq. (1.1), and solve for b to find the intercept:

$$b = y - mx \quad (1.11)$$

Use either (x_1, y_1) or (x_2, y_2) for the values of x and y in this equation. The value of b can be double-checked by reading the y -intercept directly from the graph (assuming your axes start at 0).

Example: How to find slope and intercept

Suppose you have recorded the data shown in the table for the position of an object as a function of time. You are instructed to create a graph of this data.

The first step for plotting this data is to choose scales for the two axes. The x -axis data (time) ranges from 1.0 to 5.3 seconds. So we will plot data on the x axis from 0.0 to 6.0 s. Similarly,

the y -axis data (object position) ranges from 34 to 161 mm, so we plot it over a range of 0 to 200 mm. A y -axis unit interval of ten millimeters is set to span one graph paper box. The axes are labeled with appropriate units, and a title is added to the graph. This gives us a box as shown in Plot 1.

Time (s)	Object Position (mm)
1.0 ± 0.2	34 ± 4
2.1 ± 0.3	70 ± 6
3.7 ± 0.4	108 ± 4
5.3 ± 0.4	161 ± 5

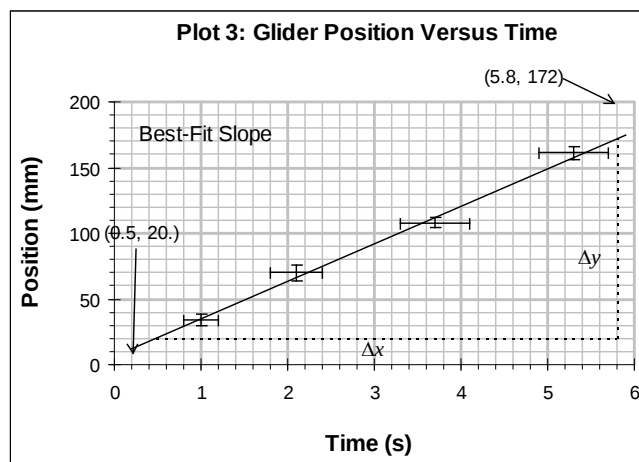
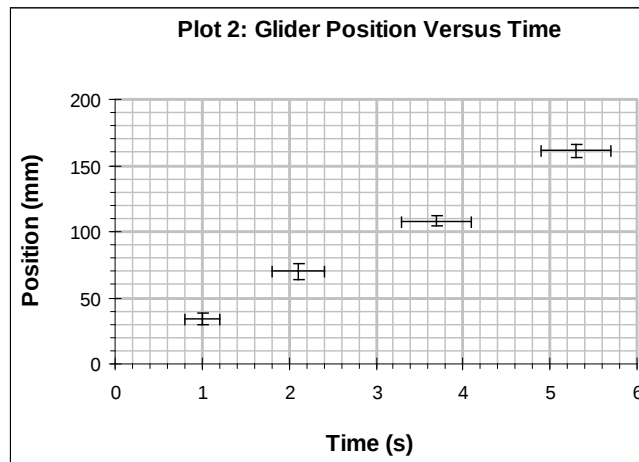
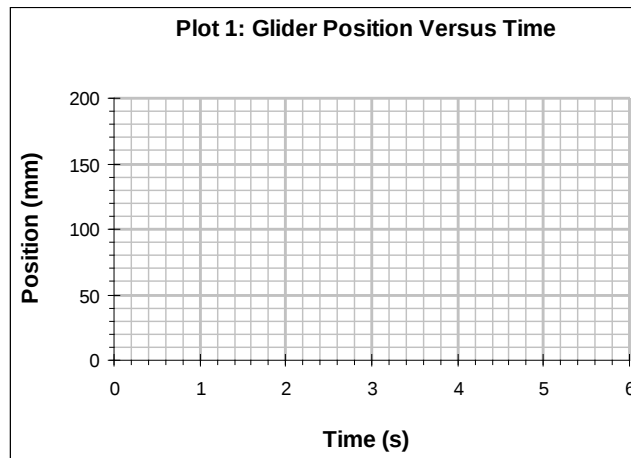
The data points are then plotted on the graph as shown in Plot 2. Horizontal and vertical bars are added to represent the uncertainty values. Inspection of the data shows that the data points appear to fall along a line. You must then determine the slope.

There are two ways to fit the data to a straight line and to compute the slope: by hand or using software that computes a “least-squares fit”. To do it by hand, we draw a line through the data points as shown in Plot 3. Two points on the line are selected with Δx as large as the graph will allow. The equation for the slope is:

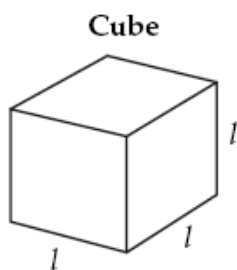
$$m = \frac{\Delta y}{\Delta x} = \frac{172. - 20. \text{ mm}}{5.8 - 0.5 \text{ s}} = \frac{0.152 \text{ m}}{5.3 \text{ s}}$$

The best-fit slope is found to be 0.029 m/s.

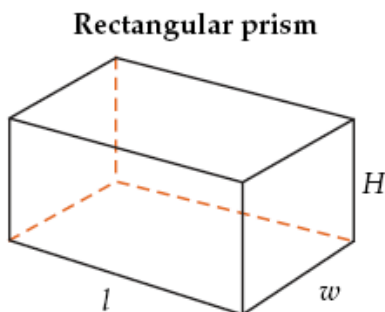
Plots to illustrate Example 7.



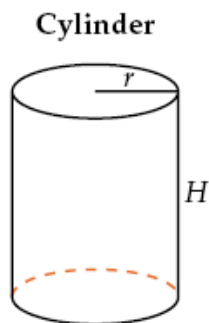
Volumes of Common Solids



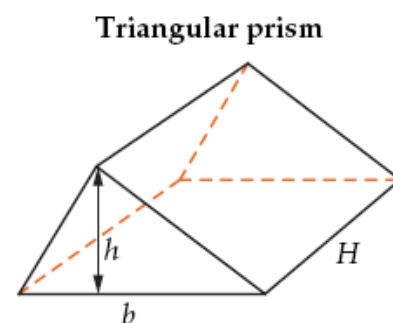
$$\begin{aligned} V &= AH \\ &= l^2 \times l \\ &= l^3 \end{aligned}$$



$$\begin{aligned} V &= AH \\ &= lw \times H \\ &= lwH \end{aligned}$$



$$\begin{aligned} V &= AH \\ &= \pi r^2 \times H \\ &= \pi r^2 H \end{aligned}$$



$$\begin{aligned} V &= AH \\ &= \frac{1}{2}bh \times H \\ &= \frac{1}{2}bHh \end{aligned}$$

Equipment List

For each setup:

1 brass rod
1 aluminum plate with hole
Set of metal rods of various lengths
Digital calipers
Meter stick

To share with everybody in room:

Precision balance
Square (to check shape of your aluminum plate).

Pre-Laboratory Question

1. If you installed larger tires on your car, your speedometer might indicate a speed that is always slower than your actual speed. Is this a problem with the precision, or the accuracy, of the speed measurement?

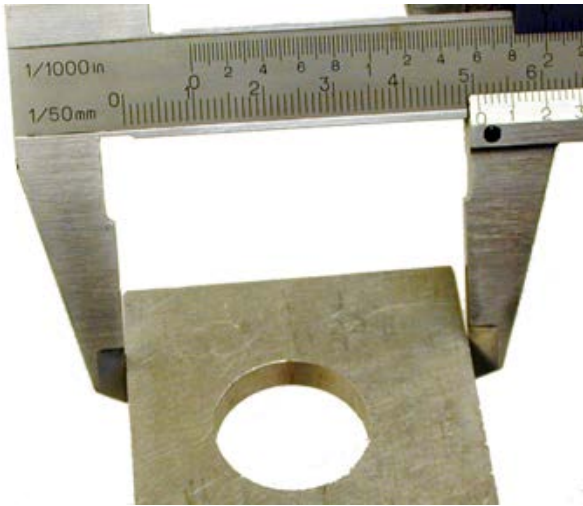


Figure A1-1. Using calipers to measure an outside dimension.

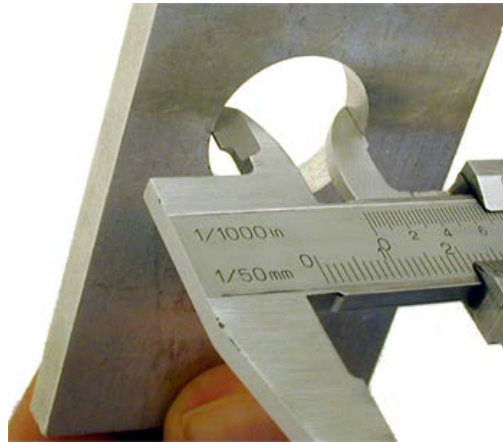


Figure A1-2. Using calipers to measure an inside dimension.

Experimental Procedure

Part I. Using Digital Calipers

You will be using digital calipers to make some of your measurements in this experiment. They are fairly simple to use, but there are a few things to keep in mind:

- Make sure that you are using the millimeter and *not* the inch scale. Press the mm/in button to switch back and forth between the two.
- Make sure that it is properly zeroed. When the caliper blades are touching, the digital display should read zero. If it does not, zero the calipers by pressing the zero button when the blades are touching.
- Refer to figures A1-1 and A1-2 for making measurements of outside and inside dimensions, respectively.

Part II. Length Measurements

- Make three independent measurements of each dimension of the brass rod and of the aluminum plate. For example, in measuring the diameter of the rod, make measurements at three different locations along its length. Make each measurement as accurately as possible using the most accurate instrument available. Record all lengths in meters.
- While making a measurement use your own best judgment to estimate the uncertainty of that measurement. The uncertainty depends not only on the instrument, but also on your ability to estimate fractions of a scale division.

Part III. Mass Measurements

- The precision balance is delicate and expensive; be gentle with it.
- Measure the mass of the brass rod and of the aluminum plate. Record all masses in kilograms.

Part IV. Calculations

- Calculate the volume of the rod and the plate. Use the average values of the dimensions in your calculations. Show your work in a SAMPLE CALCULATION.
- Calculate the densities of the rod and the plate in kg/m^3 by dividing the mass by the volume. Show your work in a SAMPLE CALCULATION.

- Compare your calculated densities with the standard values and calculate the percent error:

$$100\% \times |\text{measured value} - \text{standard value}| / (\text{standard value})$$

Use 2700 kg/m^3 as the standard value for aluminum and 8400 kg/m^3 for brass.

Part V. Graphing Data and Fitting to a Straight Line

Here you will plot the mass of some rods versus their length. The rods are all the same, except for their length, so we expect that the mass will be proportional to length.

- Measure the mass and length of at least four rods in the set.
- Using Logger Pro, enter the data for the mass and length in two different columns. In Logger Pro this is done in the “Data Table Window.”
- You can rename the axes something more meaningful than “x” and “y”. In Logger Pro this is done by double clicking on the name of the column on the data table, which brings up a window that allows you to rename the column. Rename your columns “Length (m)” and “Mass (kg)”.
- Now make a plot. In Logger Pro this happens automatically as you enter the data in the “Data Table Window” (although you may need to right click on the plot and select autoscale from zero in order to see it).
- Fit your data to a straight line using the  button.
- Print your plot (including the fit results). Print one copy for each partner. Attach your plot to your worksheet.

Part VI. Clean-up

- Exit any running software.
- Put away all equipment.
- Tidy the workbench.

Sample Calculations

Page A1-10: Calculate the volume of the rod.

Page A1-10: Calculate the volume of the plate.

Page A1-10: Calculate the density of the rod.

Page A1-10: Calculate the density of the plate.

Analysis Questions

Part I:

1. If the measurements are different, does this indicate irregularities in the sample or random errors in reading the instrument?
2. Even if numbers come out exactly even, how are 2.00 ± 0.01 and 2.000 ± 0.001 different?

Part II:

3. How do imperfections in the brass rod and aluminum plate contribute to the uncertainty?

Part IV:

4. Calculate the change in the volume of the aluminum plate:
 - (a) if the thickness is increased by 0.1 mm
 - (b) if the diameter of the hole is increased by 0.1 mm

Part V:

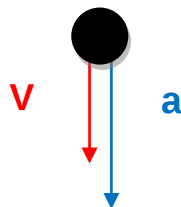
5. What does the slope of your graph tell you about the rods?

EXPERIMENT A3:

Acceleration of Gravity

$$x = x_0 + v_0 t + \frac{1}{2} a t^2$$

$$v = v_0 + a t$$



Objectives:

- Learn how to make order of magnitude estimations.
- Learn how to capture video with a digital camera.
- Learn how to analyze the physics in a video with Tracker software.

Introductory Material

Acceleration a is the rate of change of velocity v . This can be written as:

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

Acceleration has units $[\text{m/s}^2]$.

When an object undergoes constant acceleration a along a straight line, its motion can be described by two kinematic equations. First, the velocity v as a function of time t is:

$$v = v_0 + at \quad (3.1)$$

where v_0 is the velocity at time $t = 0$. Second, the position x of the object at time t is:

$$x = x_0 + v_0 t + \frac{1}{2} at^2 \quad (3.2)$$

where x_0 is the object's initial position at $t = 0$. In this experiment, you will use these kinematic equations to determine the accelerations of two different objects.

One method of finding a is to measure an object's velocity as a function of time. According to Equation (3.1), a plot of $v(t)$ is linear and the slope of the line is equal to a . A second method for finding a is to measure position as a function of time and fit it to Eq. (3.2). You will use both of these methods.

Your laboratory has an easy-to-use source of acceleration: gravity. If you drop something straight down, the acceleration a will be equal to g . This is what you will do in this experiment. You will make a video of a falling object, and then do a frame-by-frame analysis of the video to determine the acceleration of the falling object.

Physics Videos

In Part I you will make videos to measure the motion of an object.

Three coordinates are necessary to define the kinematics of an object moving in a plane: the x, y -position of the object and the time t . Digital cameras are excellent tools for studying kinematics because all three coordinates x , y , and t are simultaneously recorded in a digital movie. You will use a digital camera to make videos of moving objects in several experiments during the laboratory portion of this course.

The light-sensitive component of a digital camera is a two-dimensional array of square electronic sensors. Each sensor records the color and intensity of light for a small region of the image captured by the camera. The camera then electronically arranges the signals from all these sensors into a mosaic to make a single picture. The signal from each sensor is called a pixel, which is short for "picture element". Since the pixels are arranged in a regular square array, they serve as a sort of virtual graph paper

superimposed on the image. This greatly simplifies the task of establishing a coordinate system to determine the x,y positions of objects.

A movie is a series of pictures (or frames) taken at very regular time intervals. A series of movie frames is therefore an automatic record of the time coordinate. The camera you will use has a frame rate of ~ 30 Hz, or 30 frames per second (fps): your movies will record an object's position once every 0.033 seconds. A lot of action can happen in 0.033 seconds, but the camera's shutter is actually not open that long. The typical exposure time is $1/500^{\text{th}}$ of a second (0.002 s), which means that there are 0.031 seconds of motion *not* recorded by the camera. The actual exposure time depends on the lighting conditions in the laboratory; if lighting conditions are poor and the camera's shutter is open for a (relatively) long time, like $1/50^{\text{th}}$ of a second (0.020 s), then you will notice that moving objects appear blurred in the individual frames. Shorter exposure times are better because then measurements of time are more precise.

Terminology: “Factor of Ten” and “Order of Magnitude”

Here we introduce some mathematical terminology that physicists use. We will use this language in this experiment, and throughout the remainder of the semester. This language is intended to convey an idea of just how crude a low-precision value is.

“Factor of Ten” example: 17 and 170 are two numbers that “differ by a factor of ten.” The numbers 20 and 100 are said to be “the same, to within a factor of ten.”

“Order of Magnitude”

This means how big a number is, not precisely, but roughly. Usually it means how big it is “to within a factor of ten.” This is not a strict definition. It could mean within another factor, for example a factor of four. Usually, however, when people say “order of magnitude,” they have in mind an accuracy to within a factor of ten.

Does your answer make sense?

A basic question that all scientists ask themselves once they have completed an experiment or a calculation is whether or not the result makes sense. In physics, the two primary things for you to check are:

- Does the result have the right units?
If the answer is no, then you likely made a mistake.
- Is the value of the result clearly too big or too small?
If the answer is yes, then you likely made a mistake.

You should ask yourself these questions whenever you do laboratory work, a homework assignment, or an exam problem.

Order Of Magnitude Estimates

One method for deciding whether or not a result is clearly too big or too small is to carry out an *order of magnitude estimation*. In an order of magnitude estimation, the expected result is calculated based on simple assumptions and quick mathematics. The value obtained by an order of magnitude estimation is not very accurate, but if the assumptions are good then the value should be at least within a factor of ten of the true value. (One order of magnitude is typically *a factor of ten*, as explained above.) The order of magnitude estimation can therefore be used to assess whether an experimental result is reasonable, or whether there has perhaps been some type of gross error.

You make order of magnitude estimations all the time. If you spend twenty minutes selecting items at the grocery store and your bill at checkout is \$2,400, you are going to ask the clerk to review your bill. You suspect some type of gross error has occurred because the bill reported by the clerk is much larger than the value you expect to see based on your previous shopping experience. The same would be true if the bill came to only \$2.40, although you might be less inclined to alert the clerk.

As part of the Pre-Laboratory Questions for this course, you will practice making order of magnitude *physics* estimations to help link your everyday life experience with the numbers and units you see in your textbook, homework problems, and the laboratory. Two examples follow:

Example 1 Order of Magnitude Estimate:

Suppose that a Pre-Laboratory Question asks students to estimate the volume V of Van Allen Hall. Student A reasons: “The length of Van Allen Hall is about the same as a football field, ≈ 100 m, and the width is about one-quarter of that, or ≈ 25 m. There are seven floors in the building plus a basement, and each floor is as high as two tall people, or ≈ 4 m. Therefore the volume of Van Allen Hall should be around:”

$$\begin{aligned} V &\approx (100 \text{ m}) \left(\frac{1}{4} \times 100 \text{ m} \right) \left((8 \text{ floors}) \times \frac{4 \text{ m}}{\text{floor}} \right) \\ &\approx (100 \text{ m})(25 \text{ m})(32 \text{ m}) \\ &\approx 8 \times 10^4 \text{ m}^3 \end{aligned} \tag{3.3}$$

Student B has a different method for estimating the volume. She proposes that: “There are four cars parked along the west side of the building and fifteen cars parked along the north side. One car is ≈ 5 m long. Van Allen is across the street from St. Mary’s Church which she happens to know has a steeple 207 ft (63 m) high. Van Allen Hall is about two-thirds as tall as the steeple. Therefore:”

$$\begin{aligned}
 V &\approx \left((15 \text{ cars}) \times \frac{5 \text{ m}}{\text{car}} \right) \left((4 \text{ cars}) \times \frac{5 \text{ m}}{\text{car}} \right) \left(\frac{2}{3} \times 63 \text{ m} \right) \\
 &\approx (75 \text{ m})(20 \text{ m})(42 \text{ m}) \\
 &\approx 6 \times 10^4 \text{ m}^3
 \end{aligned}
 \tag{3.4}$$

Students A and B draw from different life experiences to make their estimates of V , but that is okay. There is no one right way to make an order of magnitude estimation, and different approaches may be equally valid. The values Students A and B obtained from their estimates were not the same, either, but the values were well within an order of magnitude of each other. Even though they got different answers, neither of their order of magnitude estimates is wrong.

Example 2 Order of Magnitude Estimate:

In Experiment M1, an easy place to make a gross error is when the glider flag length is entered into Logger Pro during Part III of the experiment. Logger Pro expects the value of the flag length L to be in meters, but most students measure L in terms of millimeters or centimeters. Suppose you found L was 5.0 cm, but you entered a value of 5 m into Logger Pro by mistake instead of 0.05 m. You then find that the approximate value of the glider's instantaneous velocity is 120 m/s, as calculated by the computer from the flag length and the photogate measurement. Without a companion order of magnitude estimation, you might not catch your gross error. The order of magnitude estimation is quick and simple. The air track is 2-m long, and the glider takes around 1 s to traverse the length.

Therefore:

$$\begin{aligned}
 v &\approx \frac{2 \text{ m}}{1 \text{ s}} \\
 &\approx 2 \text{ m/s}
 \end{aligned}
 \tag{3.5}$$

The estimate is two orders of magnitude smaller than the value of $v = 120 \text{ m/s}$ reported by the computer.

Equipment List

Meter Stick (Black and White)

Backdrop

Computer*

Digital Camera[†]

*An asterisk indicates that an item is described in the Instrument Glossary.

[†] You will need your student ID to check this item out.

Pre-Laboratory Questions

(1) ORDER OF MAGNITUDE ESTIMATION*: Estimate the velocity of an ant walking across a table. *For this question, we will guide you on how this is done.*

- State which physical quantities are applicable. *For this question, these are distance and time.*
- Write down the appropriate formula. *For this question, write down the appropriate formula for velocity.*
- State your assumptions. *For this question, state what numbers you are assuming for the distance the ant walks and how much time it takes.*
- Show your calculations and your result.

(2) ORDER OF MAGNITUDE ESTIMATION: You are going to estimate g , the acceleration of gravity. Drop an object, like a pencil for example. Without using any measuring devices, estimate the distance the object falls and the time the object takes to fall.

- Write down an appropriate formula for computing g , based on the distance the object falls and the time it takes to fall.
- State your assumptions.
- Calculate an estimate of g , based on the assumptions above. Show your calculation.

* Remember, there is no single “correct answer” when making an order-of-magnitude estimate. You must use the correct equation, but the input numbers you use will be different from another student’s. Therefore, your answer will be different from another student’s, but both might be satisfactory.

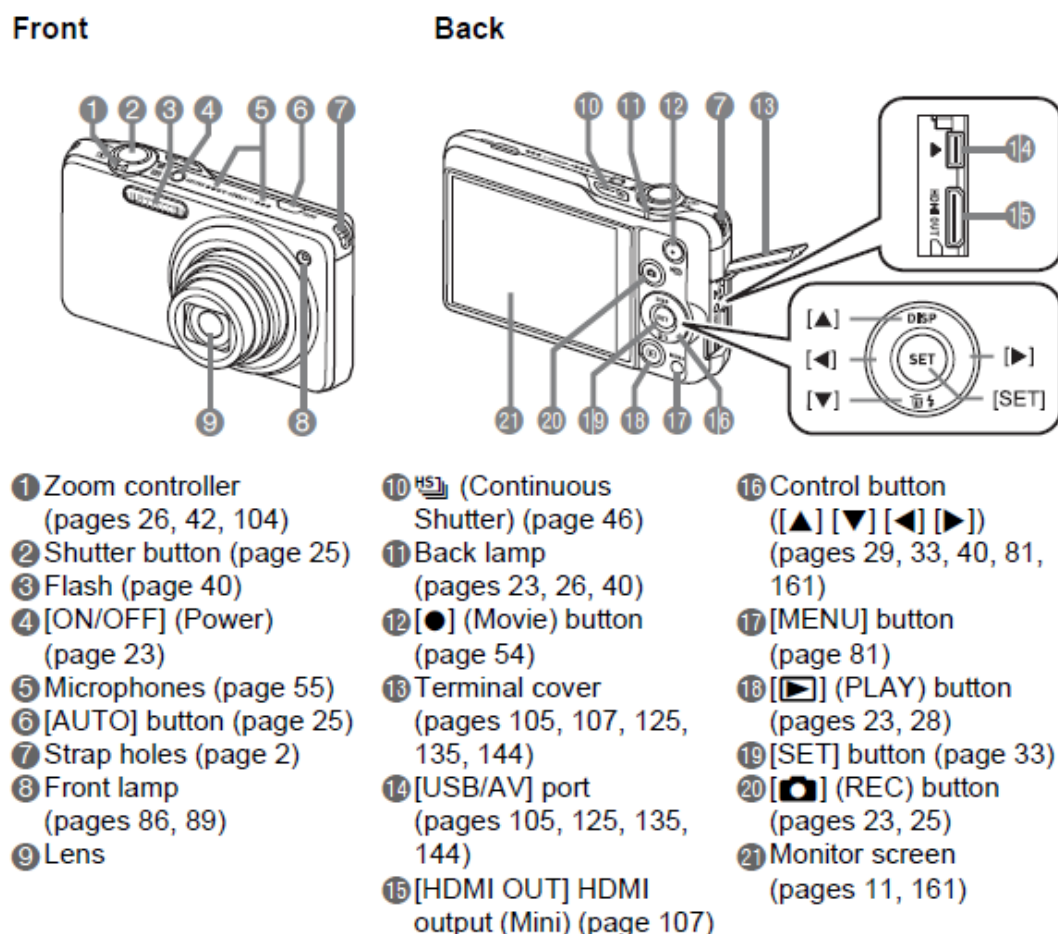


Figure 3-1. Casio EX-ZR10 digital camera.

Experimental Procedure

Part I: A Falling Object

In this part of the experiment, you will study a freely-falling object. You will use a digital movie of a small object being dropped. This physics movie will be captured on the camera's memory card and transferred to the computer.

A. Prepare the Digital Camera

The camera you will be using is a Casio EX-ZR10. Refer to Fig. 3-1 as needed while following the instructions below. The instructions will use the numbering system of Fig. 3-1. If you need further assistance in using the camera, the manufacturer's instruction manual is located on the computer's desktop: "ZR-10 English Manual.pdf".

- At this point the camera's battery should still be in the battery charger (See Fig. 3-2). Put the battery in the camera and screw it onto the camera mounting rod. You will probably have to turn the camera/mounting rod system in the clamp so that the front of the camera is parallel to the backdrop.



Figure 3-2. Battery charger (without battery).

- Turn the camera on (4) and press the REC button (20). Press the MENU button (17). Use the directional control button (16) to select the Quality tab. Scroll down to video quality and set it to HS30-240 to take a video with high speed settings, but at 30 fps. This is important. If the video quality is set to STD or FHD, the shutter speed will be too slow and your image will be blurry. If you set it to HS480 or HS240, you might get great results, but at such high frame rates the frame by frame video analysis you will do later would take too long.
- Exit the menu by pressing MENU (17) again. Zoom all the way out (1). The entire backdrop should be visible in the camera display. If it isn't, adjust the height of the camera and/or the position of the table.

B. Record the Movie

- You should now be ready to make your movie. Make sure that the black meter stick is placed vertically against the backdrop and that both ends are visible in the image.
- Press the Movie button (12) to start recording.
- Drop the ball (or whatever you use) so that it falls right next to the meter stick. Press the Movie button (12) again to stop recording.
- Unscrew the camera from the mounting rod and connect it to the computer via USB. Save your movie to the desktop, and disconnect the camera from the computer.

Exp. A3: Acceleration of Gravity

- Delete your movie from the camera by pressing the Play button (18), press right or left on the directional control button (16) until your movie is selected, then press down to delete the file.
- Turn off the camera, remove the battery, and put the battery in the charger. The red light on the charger should turn on to indicate that the battery is charging.
- Right click on the desktop icon for your movie. Click on Properties, and then the Details tab. What is the frame rate of your video? (It may not be exactly 30 fps, but it should be close, such as 28 or 29 fps). Write the frame rate down, as you will need it for the analysis.
- Your video is currently in a .MOV format, but in order to analyze it in the next section, it needs to be converted to a .mp4. Use HandBrake video conversion software to do this. See the Computer Use Glossary near the front of the manual for detailed instructions.

C. Analyzing the Video using Tracker Software

- Open Tracker. There should be a shortcut on the desktop. (Be patient, it loads somewhat slowly.)
- You must have the correct video engine settings. To do this, go to the “Edit” menu and select “Preferences.” On the “Video” tab, make sure that “Xuggle” is selected. Click “Save” to exit.
- Open your movie (the one in .mp4 format). The open option is under the “File” menu.



Figure 3-3. Screen shot of the last frame of a movie. Note the track showing the position of the ball in each frame.

- Click “Create”  and select “Point Mass.”

- Now you will create the track of the falling ball. Shift click on the ball. The position of the ball will be recorded, and Tracker will move to the next frame.
- Continue to shift click on the ball until you have a complete track. See Fig. 3-3.
- The next step is to set the scaling factor. At this point, the only spatial information contained by tracker is in pixels, and you want it to be in meters. Click on the “Show, hide or create calibration tools” button . Create a new “Calibration Stick.”
- Set the length to 1.000 and hit enter.
- Click and drag the ends of the blue calibration stick to the ends of the black meter stick in your movie.

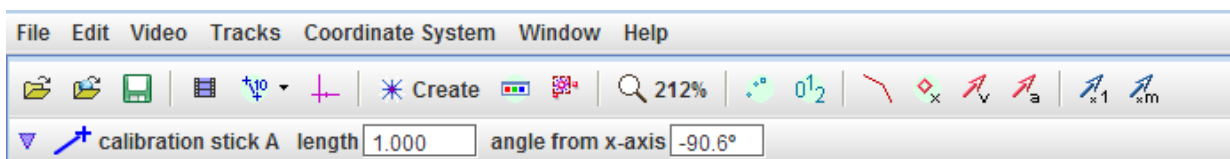


Figure 3-4. Length and angle of the calibration stick. Notice that the length is set to 1.000, and that the angle is very close to $\pm 90^\circ$.

- If you’ve done everything correctly, the angle from axis should be very close to $\pm 90^\circ$. See Figure 3-4.
- Before you can analyze the movie to obtain the acceleration of gravity, you need to set the frame rate. Click on the “clip settings” button  and change the frame rate to the value you wrote down earlier. Click OK.

According to (3.1), the relationship between the ball’s velocity and time should be linear with a slope equal to the acceleration a . You will check this and find a by creating a graph using the data you have just collected.

- To the right of the movie, you should see a plot. Click on the y-axis label, and select “vy: velocity y component.”
- The x-axis will probably be set to “time” already, but if it isn’t, click on the x-axis label and select “time.”
- Right click on the plot and select “analyze.” This will open a data tool window. Check the “Curve Fit” box in the Analyze menu to display the curve fitter. See Fig. 3-5 (a).

- In the “Fit Name” box, make sure that “line” is selected.
- Below this you will see the fit equation, which should be: $vy = a*t + b$. The parameter “ a ” is your slope, and is also the acceleration. Notice that the values of the fit parameters are shown to the right of the fit equation. Record the slope on your worksheet.
- Print your graph and close the data tool window.

Next we will find the acceleration a second way, from the position vs. time data. From Eq. (3.2), we expect the height to be a parabola with respect to time. In other words, it will be a second-order polynomial.

- Change the y-axis of the plot to “y: position y-component.” As before, the x-axis should be time.
- Right click on the plot and select “analyze” as you did before.

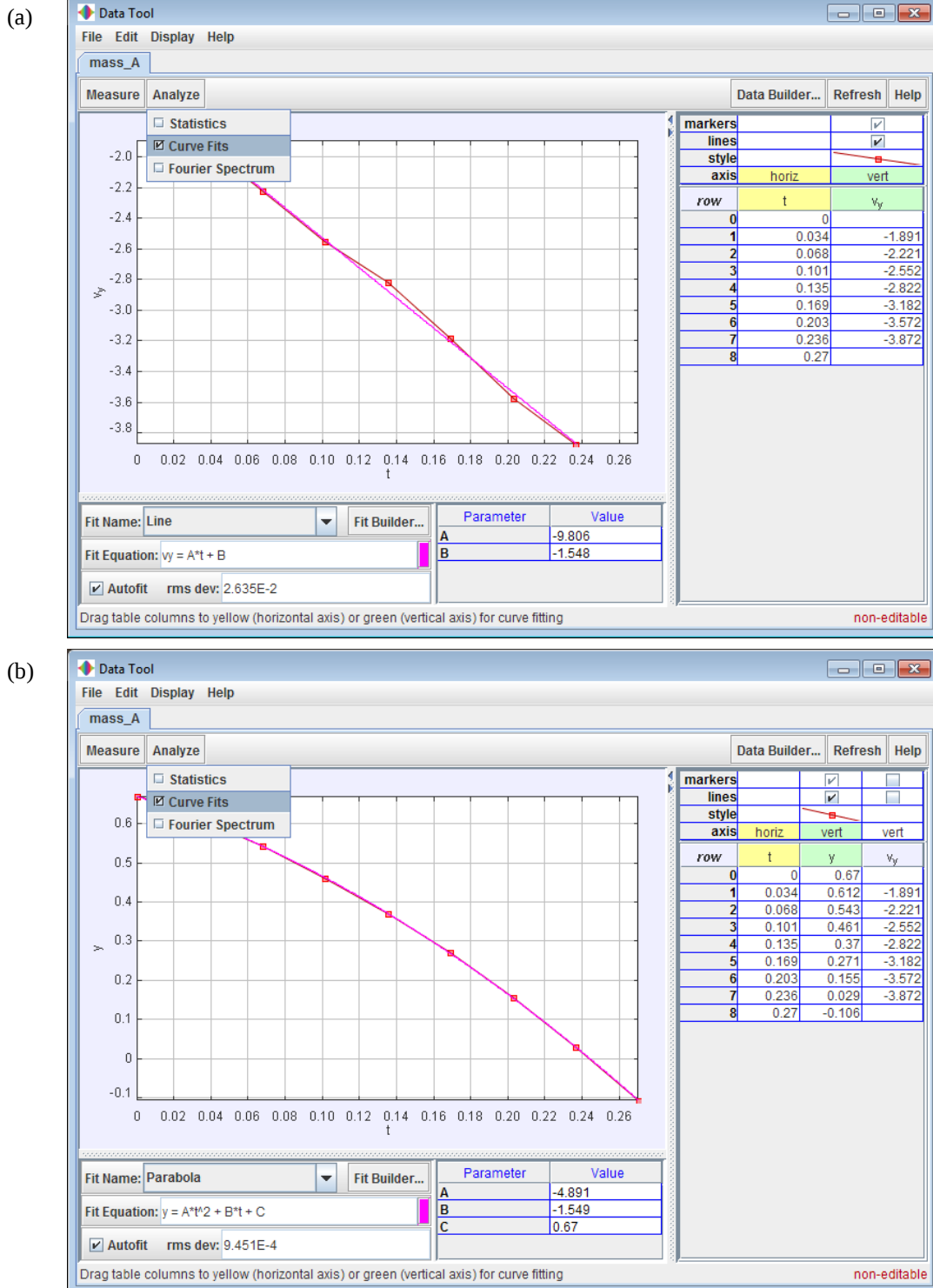


Figure 3-5. The Data Tool window. (a) Velocity vs. time. (b) Position vs. time.

- In the data table to the right, you may notice that the “vy” column is still there. If it is, uncheck “markers” and “lines” for that column so that you only have one data set on the plot to the left. See Fig. 3-5 (b).
- Change “Fit Name” to “parabola.” The fit equation should be: $y = a*t^2 + bt + c$. Once again, parameter “a” is the one of interest.

Note: It is an unfortunate labeling convention that the second order fit is called “a”, as it is not the acceleration, but $\frac{1}{2}$ the acceleration (See Eq. (3.2)).

- Record the second order fit coefficient “a” on your worksheet and determine the acceleration.
- Print your graph.

Part II: Clean Up

- Make sure that the camera battery is in the charger and that the charger is plugged in.
- Return your camera to the front of the room and get your student ID back.
- Tidy the lab bench.
- Exit any running software.

Sample Calculations Summary

NONE

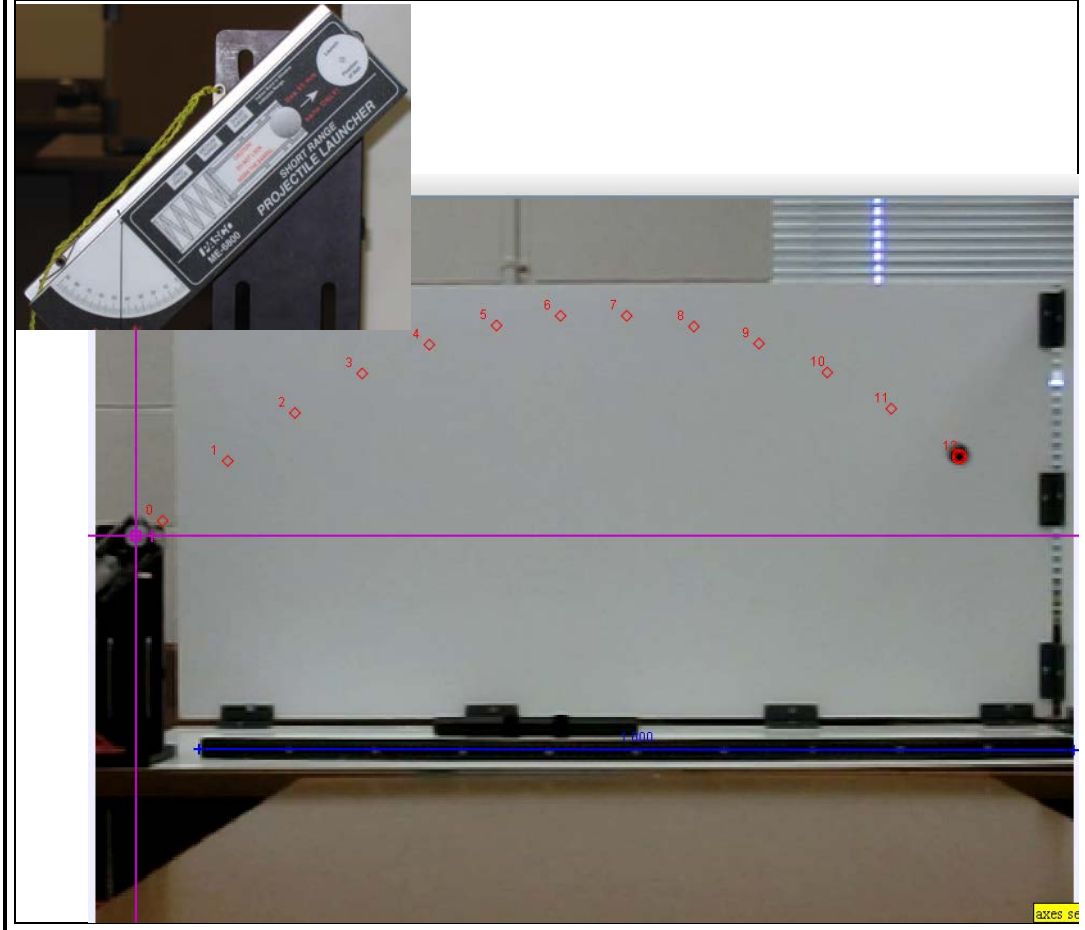
Analysis Questions

Part I: A Falling Object

1. Compare your measurement of g to the known value of 9.81 m/s^2 , indicating the percentage error calculated as $100\% \times \left| \frac{g_{\text{measured}} - g_{\text{known}}}{g_{\text{known}}} \right|$. Do this twice, for (a) velocity vs. time and (b) position vs. time fits.

EXPERIMENT A5:

Projectile Motion



Objectives:

- Understand the kinematic equations for projectile motion.
- Create movies of a flying projectile and analyze the movies to determine the muzzle velocity.
- Test your understanding of projectiles and your characterization of the launcher in a target shooting competition.

Introductory Material

The motion of an object moving in two-dimensional space with constant acceleration is described by the following kinematic equations:

$$\begin{aligned}x &= x_0 + v_{x0}t + \frac{1}{2}a_{x0}t^2 & y &= y_0 + v_{y0}t + \frac{1}{2}a_{y0}t^2 \\v_x &= v_{x0} + a_{x0}t & v_y &= v_{y0} + a_{y0}t \\a_x &= a_{x0} & a_y &= a_{y0}\end{aligned}\tag{5.1}$$

In these equations, t is time, x is the horizontal position coordinate and y is the vertical position coordinate. Here, v_x and a_x are the velocity and acceleration of the object along the x -coordinate, and x_0 , v_{x0} , and a_{x0} are the object's initial x -coordinate position, velocity, and acceleration. The variables v_y , a_y , y_0 , v_{y0} , and a_{y0} have the corresponding meanings for the y -coordinate.

You will be studying the two-dimensional motion of a projectile launched on the surface of the earth. There is no acceleration along the horizontal direction (the x -coordinate) for this case. The acceleration along the vertical direction (the y -coordinate) is the gravitational acceleration. Here, we choose to define g to be *positive*: $g = +9.81 \text{ m/s}^2$. Note the sign.

$$\begin{aligned}a_x &= a_{x0} = 0 \\a_y &= a_{y0} = -g\end{aligned}\tag{5.2}$$

Note that a_y is a negative number, because we defined g to be positive.

With these substitutions, the position and the velocity equations for the projectile's motion simplify to:

$$\begin{aligned}x &= x_0 + v_{x0}t & y &= y_0 + v_{y0}t - \frac{1}{2}gt^2 \\v_x &= v_{x0} & v_y &= v_{y0} - gt\end{aligned}\tag{5.3}$$

The origin of the coordinate system, $(0, 0)$, can be set anywhere in the plane of the projectile's motion. It is convenient to put the origin at the point of launch, the initial position of the projectile (x_0, y_0) . Then $x_0 = 0$ and $y_0 = 0$, so Equations (5.3) becomes:

$$\begin{aligned}x &= v_{x0}t & y &= v_{y0}t - \frac{1}{2}gt^2 \\v_x &= v_{x0} & v_y &= v_{y0} - gt\end{aligned}\tag{5.4}$$

The muzzle velocity vector $\mathbf{v}_0$ makes an angle θ with the ground (the x -coordinate). Using trigonometry, the x,y -component vectors of the muzzle velocity, $\mathbf{v}_{x0}$ and $\mathbf{v}_{y0}$, have magnitudes of:

$$\begin{aligned}v_{x0} &= |\mathbf{v}_{x0}| = v_0 \cos \theta \\v_{y0} &= |\mathbf{v}_{y0}| = v_0 \sin \theta\end{aligned}\tag{5.5}$$

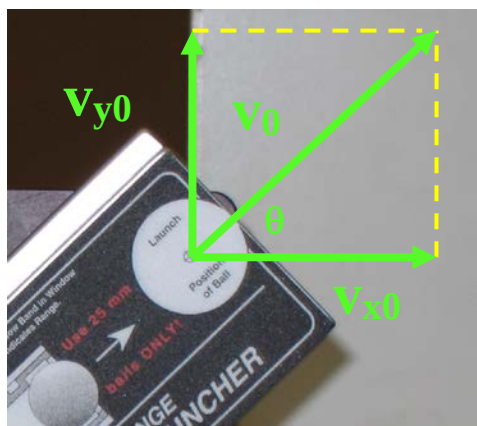


Figure 5-1. Breaking the velocity into x and y components.

Pre-Laboratory Questions

1. The projectile launcher is set to an angle of 45° . After analyzing the video, it is determined that $v_{x0} = 2.07 \text{ m/s}$. Calculate v_0 .
2. Explain the purpose of the black meter stick in this experiment.

Equipment List

Backdrop	Ramrod for Projectile Launcher
Carbon Paper	Safety Glasses
Computer*	Table Clamps
Meter Stick (Black and White)	Digital Camera*
Projectile Launcher*	
White Paper with Bullseye	
Projectiles	

* An asterisk indicates that an item is described in the Instrument Glossary.

Experimental Procedure

SAFETY WARNING:

Projectiles will fly through the air during this experiment.

You MUST wear eye protection at all times.

Part I: Characterize the Projectile Launcher

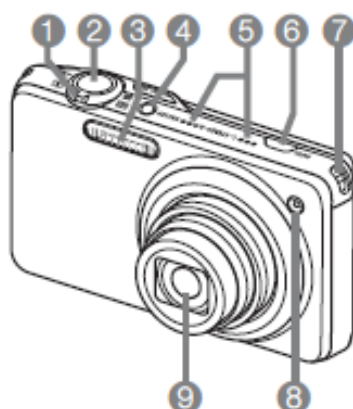
You will record digital movies of your projectile launcher shooting a ball. You will analyze these movies to determine the muzzle velocity v_0 and the experimental range. The experimental range tends to be less than the theoretical range.

As in Experiment A3, you will capture your physics movies with a Casio EX-ZR10 digital camera (Fig. 5-2).

Prepare the Projectile Launcher and Backdrop:

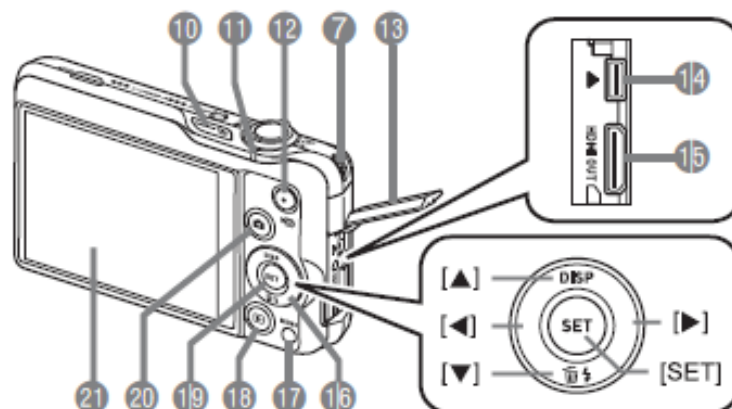
- The backdrop should be on the lab bench, and should be parallel with the lab wall. Attach the projectile launcher to the bench with the table clamp. Snug the edge of the backdrop floor up to the launcher base.
- Take a moment to align the camera to assure it is perpendicular to the backdrop.

Front



- ① Zoom controller (pages 26, 42, 104)
- ② Shutter button (page 25)
- ③ Flash (page 40)
- ④ [ON/OFF] (Power) (page 23)
- ⑤ Microphones (page 55)
- ⑥ [AUTO] button (page 25)
- ⑦ Strap holes (page 2)
- ⑧ Front lamp (pages 86, 89)
- ⑨ Lens

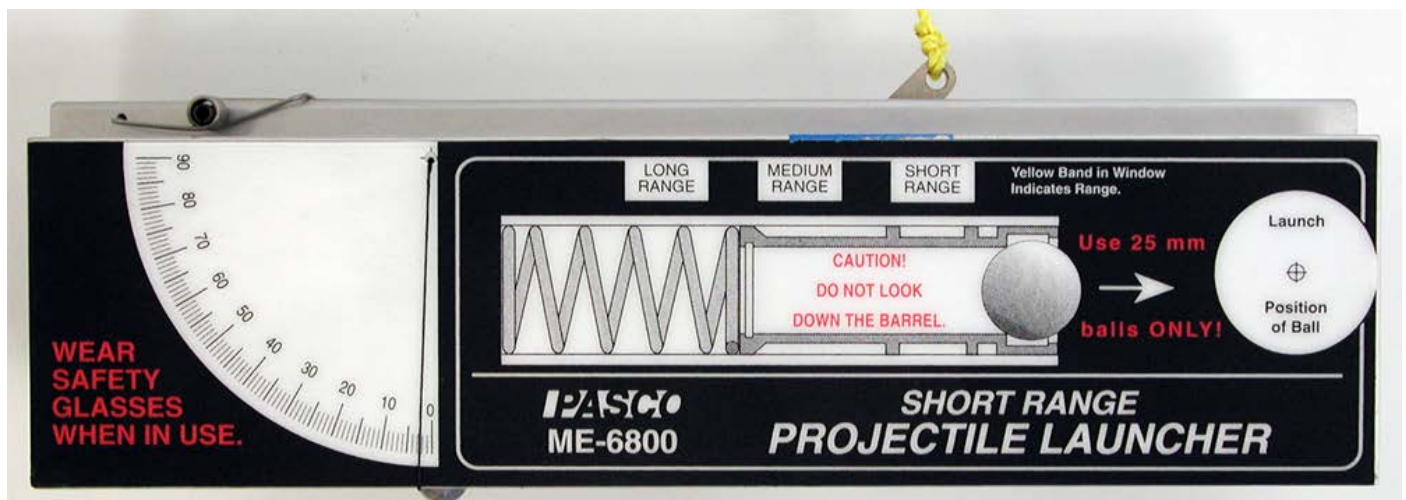
Back



- ⑩ (Continuous Shutter) (page 46)
- ⑪ Back lamp (pages 23, 26, 40)
- ⑫ (Movie) button (page 54)
- ⑬ Terminal cover (pages 105, 107, 125, 135, 144)
- ⑭ [USB/AV] port (pages 105, 125, 135, 144)
- ⑮ [HDMI OUT] HDMI output (Mini) (page 107)
- ⑯ Control button ([▲] [▼] [◀] [▶]) (pages 29, 33, 40, 81, 161)
- ⑰ [MENU] button (page 81)
- ⑱ (PLAY) button (pages 23, 28)
- ⑲ [SET] button (page 33)
- ⑳ (REC) button (pages 23, 25)
- ㉑ Monitor screen (pages 11, 161)

Figure 5-2. Casio EX-ZR10 digital camera.

Exp. A5: Projectile Motion



Projectile launcher. The ball comes out of the right side.



The launcher angle, adjusted to 45°.



The black and white meter stick, which is used to calibrate distance in the video, is positioned under the trajectory of the ball.

Figure 5-3. Different views of the launcher.

- Set the launcher angle to 45° .
- Place the ball in the muzzle.
- Adjust the position of the launcher so that the ball flies parallel to the backdrop.
- Position the black and white meter stick as shown in the photo, so that it is parallel to the longest side of the backdrop and underneath the ball's trajectory.

The launcher has short, medium, and long ranges. The range is determined by how far you push the ball in with the ramrod.

SAFETY WARNING:

- USE ONLY THE SHORT-RANGE SETTING. The medium and long ranges are too dangerous for a crowded laboratory.
- USE COMMON SENSE TO DECIDE WHETHER IT IS SAFE TO LAUNCH THE BALL. Make sure your lab partner is not in the way.

- You should hear a click when the muzzle locks in place.
- Make sure that nobody is in the way before launching. Make a test launch. To launch the ball, pull up on the yellow string.
- Make sure to record your incline angle in your lab report and make sure the launcher is secure.

Making a Physics Video of Projectile Motion:

- Use the Casio EX-ZR10 digital camera to record the projectile motion of the ball as it is launched. Refer to Part I of Experiment A3 for a detailed step-by-step procedure for recording video with this camera.
- A few specific things to keep in mind for this experiment:
 - Make sure the camera includes the entire area to be recorded. If it doesn't, move the camera, the table, or both.
 - Make sure that the white circle on the launcher is included, as you will later set this point to be (0,0).
 - You also need to see both ends of the meter stick, as it will be needed for scaling purposes.

Exp. A5: Projectile Motion

- Fine-tune the camera's position so that the projectile launcher and backdrop are centered within the frame of the movie.
 - The camera should be pointing straight towards the backdrop, not at an angle.
- Unscrew the camera from the mounting rod and connect it to the computer via USB. Save your movie to the desktop, and disconnect the camera from the computer.
- Delete your movie from the camera by pressing the Play button (18), press right or left on the directional control button (16) until your movie is selected, then press down to delete the file (See Figure 5-2 for location of buttons).
- Turn off the camera, remove the battery, and put the battery in the charger. The red light on the charger should turn on to indicate that the battery is charging.
- Right click on the desktop icon for your movie. Click on Properties, and then the Details tab. What is the frame rate of your video? (It may not be exactly 30 fps, but it should be close, such as 28 or 29 fps). Write the frame rate down, as you will need it for the analysis.
- Your video is currently in a .MOV format, but in order to analyze it in the next section, it needs to be converted to a .mp4. Use HandBrake video conversion software to do this. See the Computer Use Glossary near the front of the manual for detailed instructions.

Data Analysis:

You will now use Tracker to find the muzzle velocity v_0 of the projectile launcher, and to compare the theoretical range of the launcher with your experimental value. You should start Tracker once you have edited and copied your movie and enter the points as you did in Exp A3. If you don't remember how to do this (or if you didn't do Exp A3), the general procedure is given in Exp A3. Instructions that are more specific to this experiment are given below:

- You must have the correct video engine settings. To do this, go to the "Edit" menu and select "Preferences." On the "Video" tab, make sure that "Xuggle" is selected. Click "OK" to exit.
- Open the .mp4 version of your movie in Tracker.
- Use the mouse to record the ball positions in each frame, beginning with the first frame AFTER the ball leaves the muzzle.
- Right click near the slider under the movie and select "Set time to zero."

- Change the Origin. Click on “Show or hide coordinate axes” . Click on the origin (the intersection of the purple lines) in the movie window. Drag it to the white circle on the projectile launcher muzzle labeled “Launch Position of ball”. (Of course you can’t read this in your movie image, but you can still see the white circle.)
- Set the scale factor. (See Exp A3 for instructions on how if you have forgotten.) 
- Save your work so far. Give the file a name that indicates the launch angle.
- According to (5.4), the relationship between the ball’s x -coordinate and time should be linear with a slope equal to v_{x0} . You will check this and find v_{x0} by creating a graph using the data you have collected.
- On the plot to the right of the movie, set the y -axis to “ x : position x -component” and the x -axis to “time” (these are the default options, so you probably won’t have to change anything, but if you do need to change an axis, just click on the axis label).
- Right click on the plot and select “analyze”.
- Check the “Curve Fit” box in the Analyze menu to show the curve fitter.
- The “Fit Name” should be “linear”, and the fit equation should be $x = a*t + b$.
- Print the graph and turn it in with your lab report.
- The slope of the line, a , is v_{x0} . Record this value in your lab report.
- Close the Data Tool window.
- Use the value of v_{x0} , the launch angle and Eq. (5.5) to find the initial muzzle velocity, v_0 . Show your work in a SAMPLE CALCULATION. Record this value in your Lab Report.

You will test your data to see if it fits Eq. (5.3), $v_y = -gt + v_{y0}$, where $v_{y0} = v_0 \sin \theta$ from Eq. (5.5).

- Plot v_y vs. t . using the data you have collected. The procedure is the same as above, except that you will change the y -axis to “ v_y : velocity y -component”. (Click on the y -axis label to change it.)

- ❑ Your “Fit Name” will once again be “linear”. If the fit is good, that confirms Eq. (5.3). The slope of the line is your measurement of the acceleration g .
- ❑ Print the graph and turn it in with your lab report.
- ❑ Report the values for the acceleration g and the y -component of the muzzle velocity v_{y0} obtained from the fit parameters of your plot.
- Additional trials: Continue making and analyzing projectile launches for other values of θ at 30° and 60° until the TA says it is time to begin the target shooting contests. You do not need to show your work again in sample calculations.

Part II: Target Shooting #1: Predicting the Range

The target is a series of concentric rings, and each ring is worth a certain number of points. You will fix the launcher angle, calculate the range to the center of the target, and then tape the target at your calculated position. You get five shots to earn as big a score as possible. You can alter your target position after each shot.

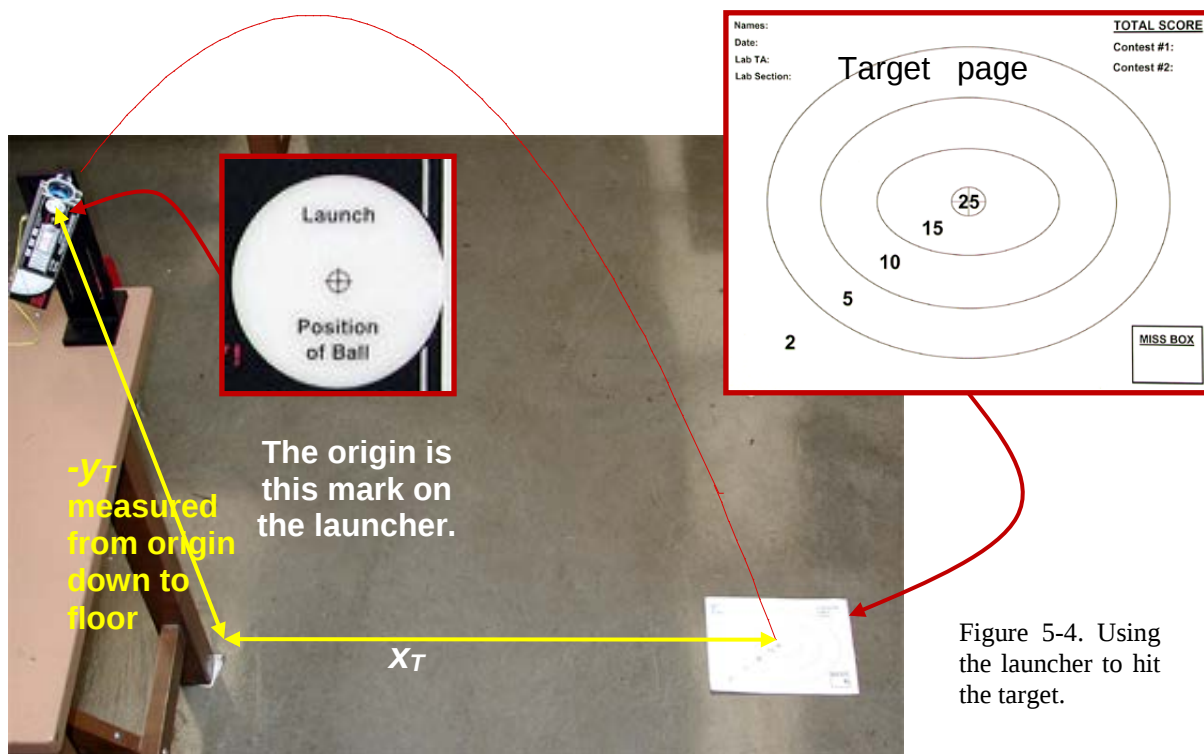
- Set the angle of your launcher to 45° . Measure y_T , the vertical distance from the launcher muzzle to the floor. IMPORTANT: In your coordinate system, y_T will be a negative number.
- The following equations can be derived from the kinematic equations:

$$t_T = \frac{v_{y0} + \sqrt{v_{y0}^2 - 2gy_T}}{g}, \quad \frac{v_{y0} - \sqrt{v_{y0}^2 - 2gy_T}}{g}.$$

Use these to find out how long the ball is in the air, t_T . Show your work in a SAMPLE CALCULATION.

- Use t_T to find out how far the ball will travel using $x_T = v_{x0}t_T$, where x_T is how far away from the launcher the ball will hit the floor.

- Place your target a distance x_T away from the launcher and do your best to aim the launcher's muzzle in the direction of the target's center. Clamp the launcher to the table, Place the carbon paper on the target, and shoot. **DO NOT TAPE THE CARBON PAPER TO THE TARGET.**



- Check to see where you hit. If you completely missed, put an “X” in the “Miss” box on the target sheet.
- Making a correction to the target position and shoot again. Repeat up to 5 trials, or until you hit the target, whichever comes first. Record the corrections you make and the results of your trials in your Lab Report.

Part III: Target Shooting #2: Predicting the Launch Angle

For this contest, you will position the launcher at the edge of the table. The target should be taped on the floor ~ 1.25 m from the launcher. You get five shots to earn as big a score as possible. You can alter your launcher angle (do not change the distance to the target) and its orientation after each shot.

- First guess an initial angle.
- Circle the hits on the target from Part II to distinguish them from this contest.

- Set your launch angle at θ and do your best to aim the launcher's muzzle in the direction of the target's center. Clamp the launcher to the table, place the carbon paper on the target, and take a shot. **DO NOT TAPE THE CARBON PAPER TO THE TARGET.**
- Check to see where you hit. If you completely missed, put an "X" in the "Miss" box on the target sheet. Take four more shots, making corrections to the launch angle and orientation as you see fit. Record the corrections you make and the results of your five trials in your Lab Report.

Part IV: Clean Up

- Make sure that the camera battery is in the charger and that the charger is plugged in.
- Return your camera to the front of the room and get your student ID back.
- Tidy the lab bench.
- Exit any running software.

Sample Calculations Summary

Part I: Characterize the Projectile Launcher

Page A5-9: v_0

Part II: Target Shooting #1: Predicting the Range

Page A5-10: t_T

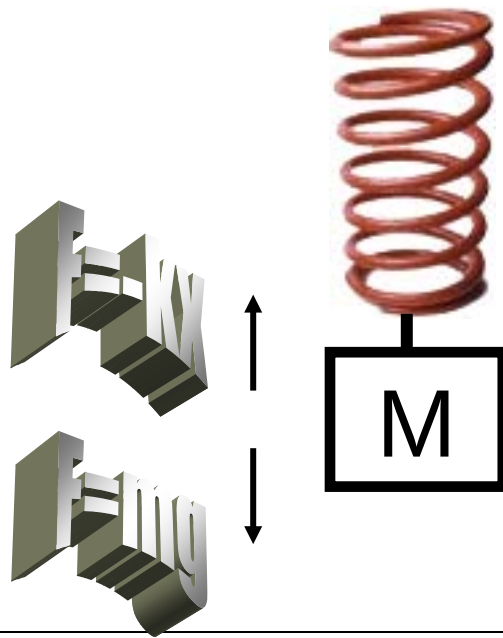
Analysis Questions

Part I: Characterize the Projectile Launcher

1. Compare your measurement of g to the known value of 9.81 m/s^2 , indicating the percent error calculated as $100\% \times \left| \frac{g_{\text{measured}} - g_{\text{known}}}{g_{\text{known}}} \right|$.
2. At what launch angle should you tilt the launcher to shoot the ball as high as possible? Why? Calculate the maximum height your launcher will shoot the ball. Use your average muzzle velocity for this calculation.

EXPERIMENT A4:

Hooke's Law & Simple Harmonic Oscillators



Objectives:

Spring:

- Study Hooke's Law describing the restoring force exerted by a spring.
- Measure the period of oscillation for a spring and compare this measured value to the theoretical value based on Hooke's spring constant.

Pendulum:

- Measure the period of oscillation of a simple pendulum and compare it to its theoretical value.
- Verify that the period of the pendulum is independent of the mass on the end of the pendulum.

Introductory Material

Springs

According to Hooke's Law, a stretched spring experiences a restoring force

$$F = -kx \quad (4.1)$$

where k is the spring constant that depends on the composition and curling of the spring, and x is the distance from the spring's equilibrium position. The negative sign indicates that the force is in the opposite direction as the displacement of the spring.

Let's consider the ideal case where no external forces act on the spring (no friction, no air resistance, etc.). If the spring is stretched to a position $x = A$, the restoring force will cause the spring to move through the equilibrium point, and out to a position $x = -A$. In this ideal case, the spring will continue to oscillate between A and $-A$ forever (Of course in the real world, external forces such as friction always exist to some degree, and the spring will eventually stop moving). A is referred to as the amplitude of the oscillation, and is the maximum displacement of the spring from the equilibrium position.

The period of oscillation is given by

$$\tau = 2\pi\sqrt{m/k} \quad (4.2)$$

where τ is the period, and m is the mass attached to the end of the spring. The period is the length of time it takes for the spring to move from A to $-A$ and back to A .

Pendulum

Another thing that oscillates is a pendulum. A *Simple Pendulum* is any straight rotation arm and a mass at the end. Pendulums oscillate back and forth when pulled small distances from their equilibrium position. Thus old-fashioned clocks kept time, based upon the period of oscillation of the pendulum. The period of the simple pendulum depends only on the length of the rotation arm. The period is

$$\tau = 2\pi\sqrt{l/g} \quad (4.3)$$

where l is the length of the pendulum's arm and $g = 9.8 \text{ m/s}^2$ is the acceleration due to gravity.

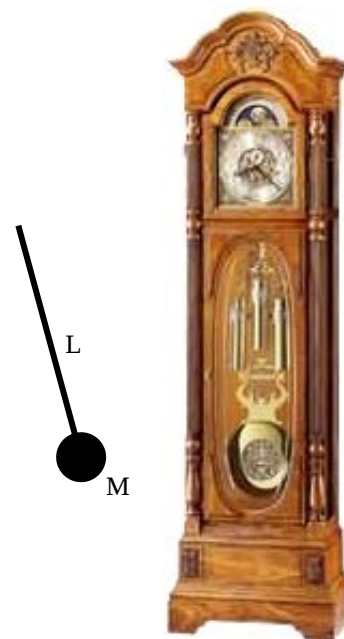


Figure 4-1. A pendulum consists of a mass M hanging a length L below a pivot. Gravity causes it to swing. A grandfather clock has a simple pendulum, which regulates the speed of the clock.

Equipment List

Brass spring
Set of hanging weights
Motion detector
String to make a pendulum
Stopwatch
Ruler

Pre-Laboratory Questions

1. Suppose you have a bathroom scale that uses a spring that deflects a distance $x = 0.1 \text{ mm}$ ($= 0.0001 \text{ m}$) when a person of mass $m = 100 \text{ kg}$ steps on it.
 - First calculate the weight $F = mg$ of the person.
 - Then calculate the spring constant K of the bathroom scale; be sure to use SI units (m, not mm) and include the units.
2. Suppose you were in a hammock, where your body was in the center, and it hangs down a distance $l = 0.5 \text{ m}$ below the points where the ends of the hammock are supported. This will be like a pendulum.
 - (a) Calculate the period τ of the pendulum; be sure to include the units.
 - (b) Does it matter how much you weigh?

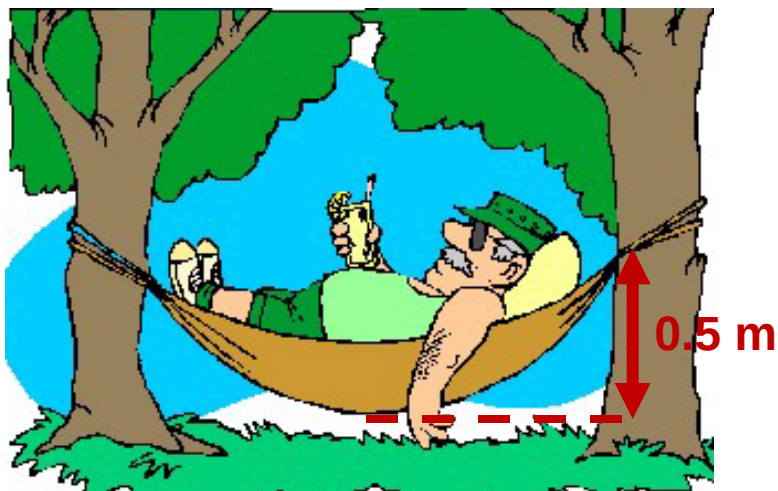


Figure 4-2. Hammock described in Pre-Laboratory Question #2.

Experimental Procedure

Part I. The Spring

1. Hang the larger end of the spring from the hook.
2. Measure the length of the hanging spring with no mass attached.
3. Hang a 100 g (0.1 kg) mass from the spring. Measure the length of the spring and record it on your worksheet. Subtract the length of the spring without any masses from the length of the spring with the mass attached and record this in the "Net Length Change" column on your worksheet. Remember to record it in meters.
4. Calculate the force of the hanging mass using $F = mg$.
5. Repeat the previous two steps for the rest of the masses listed on the worksheet.
6. You will note that the formula $F = -kx$ has the form $y = mx + b$, which is the equation of a straight line. In this case the slope m is $-k$.
 - Using Logger Pro, plot the net length change x on the x axis and the force on the y axis.
 - Fit your data to a straight line. Do this by pressing the  button.
 - The slope is the spring constant k . Record it on your worksheet. (Why not $-k$? Well, what you actually measured was the force needed to stretch the spring, which is equal and opposite to the restoring force. It is the restoring force which has the minus sign.)
7. Print your graph and close Logger Pro.
8. Find the mass of the rod and plastic flag and record it on your worksheet.
9. Also find the mass of the spring and record it on your worksheet.
10. Now attach the rod and plastic flag to the free end of the spring.
 - Stretch the spring a small distance downward and release it.
 - Watch it oscillate, and try to get a feel for a good distance of stretching that gives a nice smooth oscillation.
11. Connect the motion detector to the DIG/SONIC1 port of the LabPro (or LabQuest Mini) device, and restart Logger Pro. Put the motion detector on the floor so that it can detect the position of the plastic flag on the end of the rod.
12. Zero the motion detector (Ctrl-0).

13. Once again stretch the mass on the spring out to the distance you decided worked best in the previous step.
 - Hit collect. The data should look like a relatively smooth wave. If the data is too jagged or irregular, it is likely that you need to adjust the position of the motion detector.
14. The time from one peak to the next is the period of oscillation. To get a better value for the period, τ take the time it takes for four complete oscillations and divide by 4. This yields the measured period τ of the spring. If you do not have at least 4 complete oscillations, you can increase the data acquisition time. To do this, click on the Data Collection button .
15. Use Eq. 4.2 to calculate the theoretical value of τ . This equation assumes a massless spring. However, your spring has mass and that needs to be accounted for. To correct for the mass of the spring, use the mass of the rod and flag plus 1/3 of the mass of the spring in your calculation.
16. If the motion detector was properly zeroed, the amplitude A of your oscillation can be easily read off of the displacement vs. time graph. It is simply the y coordinate of any peak. Record A on your worksheet. Note that the amplitude does decrease over time due to frictional forces.

Part II. The Simple Pendulum

1. Cut a length of string. Tie one end to the hook and tie the other end to a small mass. Measure the pendulum length l as the distance from the upper point where the string is tied to the middle of the mass, as shown in the figure.
2. Swing the mass back a small distance from its resting position. The important thing is that the oscillation distance be small compared to the length of the string, for example 1/5 to 1/10 the length of the string.
3. Be sure the pendulum swings smoothly and in a plane (i.e., you only want it going back and forth in one direction, not in circles).
4. Time the pendulum's oscillation:
 - Release the pendulum.
 - After a couple of oscillations, start the stopwatch at one of the turning points where it reaches its maximum height.
 - Stop timing after 10 complete oscillations. See Figure 4-4.
5. Calculate the period by dividing the time by the number of oscillations.

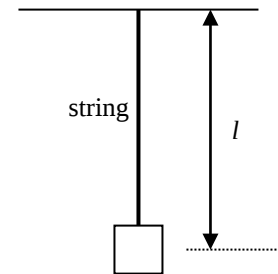


Figure 4-3. Simple pendulum of length l .

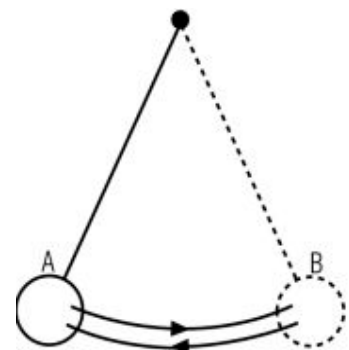


Figure 4-4. To make 1 complete oscillation, the mass must travel from position A to position B, and BACK to position A.

6. Repeat this for 2 more trials of the same length.
7. Repeat steps 1 through 6 for a second mass.
8. Repeat steps 1 through 7 for a second length of string.
9. Calculate the theoretical period, τ for each string length using Eq. 4.3.

Sample Calculations Summary

Part I: The Spring

Page A4-5: Theoretical value of τ (spring)

Part II. The Pendulum

Page A4-5: Theoretical value of τ (pendulum, first string only)

Analysis Questions

Part I. The Spring

1. Compare the theoretical and calculated values of τ . Do this by calculating the percent error:

$$100\% \times |(\text{measured value} - \text{theoretical value}) / (\text{theoretical value})|.$$

Part II. The Pendulum

2. Compare the experimental result to the theoretical period for each string by calculating the percent error.
3. Does changing the mass affect your measured period of oscillation? Does changing the length of the string change your measured period of oscillation? Explain why this makes sense (Hint: look at Eq. 4.3).

Conversion and Conservation of Energy



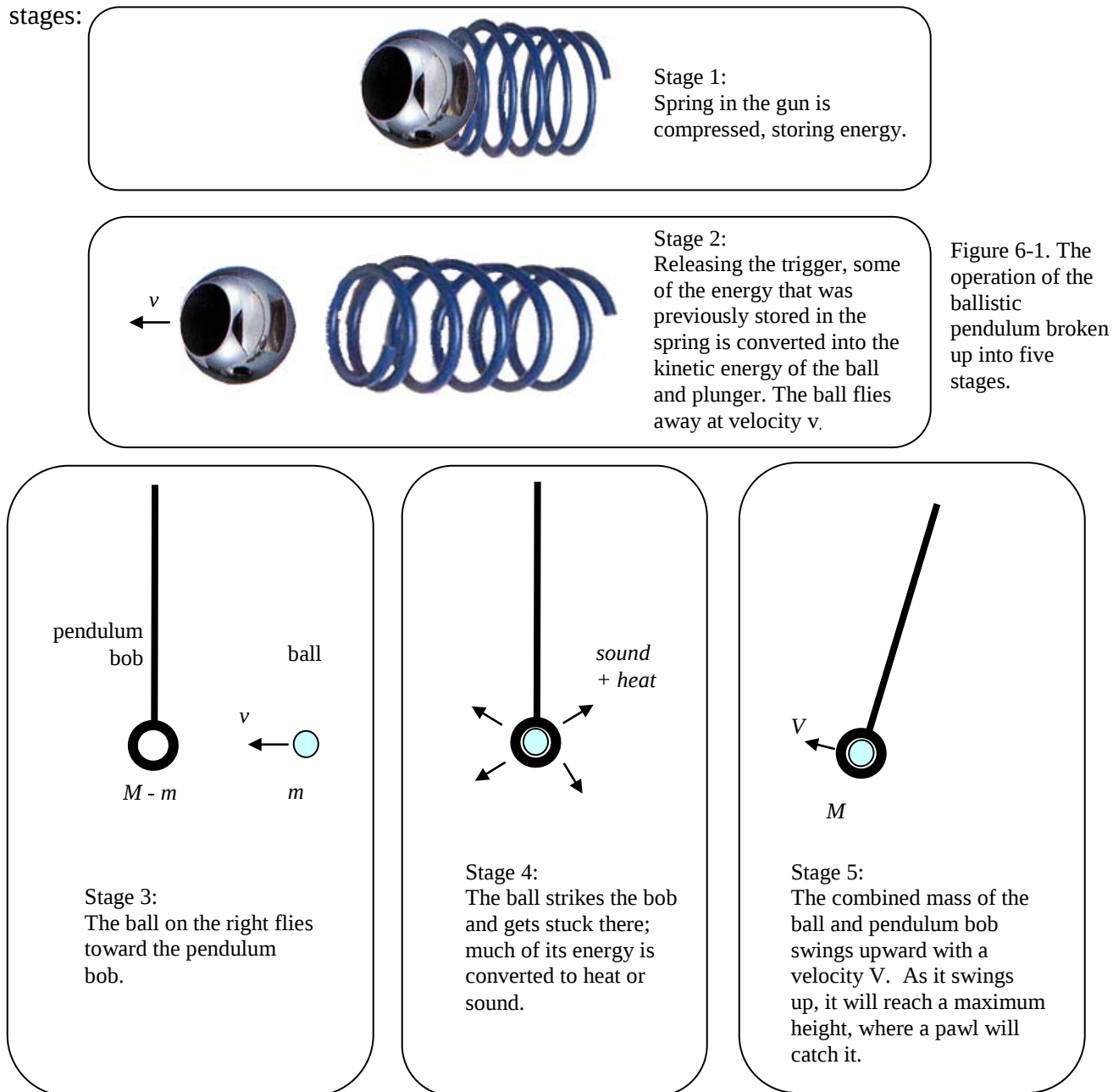
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Adapted from Experiment M5:
Conversion and Conservation of Energy
by Anthony Moeller

Introductory Material

The principle of conservation of energy states that energy can neither be created nor destroyed¹. Energy can only be converted into other forms of energy. You have probably encountered kinetic and potential energy at this point in your studies, but there are many other forms of energy as well, such as heat, sound, chemical and electrical energy.

In today's experiment, you will use a ballistic pendulum to study conversion and conservation of energy. We can view the operation of the ballistic pendulum as having five stages:



¹ The Theory of Special Relativity actually requires this to be the conservation of mass-energy, but that is beyond the scope of this experiment.

Stage 1

In Stage 1 you will cock the gun, compressing the spring. During this stage, all of the energy in the system is potential energy stored in the spring. The potential energy stored in a spring is:

$$U_{\text{spring}} = \frac{1}{2} kx^2, \quad (6.1)$$

where k is the spring constant and x is the distance the spring is compressed. While we could devise a method to measure both k and x and thus determine U_{spring} , we will not do so today.

Stage 2

In Stage 2 you will fire the gun. Firing the gun converts the potential energy of the spring to kinetic energy due to the moving plunger/spring/ball system. Note that not all of the spring's energy is converted to kinetic energy, as some of it is converted to heat and sound. This kinetic energy of Stage 2 would be given by:

$$K_{\text{gun}} = \frac{1}{2} m_{\text{gun}} v^2 \quad (6.2)$$

where m_{gun} is the mass of the moving parts of the gun (spring, plunger, etc.) and v is the velocity of the plunger. If we were to take the trigger assembly apart, we could find m_{gun} to help us find K_{gun} , but we will not do so today to ensure that we do not lose any pieces of the trigger assembly.

Stage 3

In Stage 3 the ball is free of the plunger and is moving towards the pendulum bob. During Stage 3, all of the energy in the system is the kinetic energy of the flying ball, and is simply given by:

$$K_{\text{ball}} = \frac{1}{2} mv^2 \quad (6.3)$$

where m is the mass of the ball and v is the velocity of the ball. Note that v in Eq. 6.3 is the same as that in Eq. 6.2, as the plunger and ball are assumed to move at the same speed. You will begin your energy measurements in Stage 3, as you will use a balance to record the mass of the ball, and you will measure the velocity of the ball using two photogates.

Stage 4

In Stage 4 the ball collides with the pendulum bob. As the ball and bob stick together, the collision is said to be an *inelastic collision*². As you may not have encountered collisions yet at this point in the course, here are a few important comments specifically about inelastic collisions:

² If the ball and bob did not stick together and instead bounced off of each other, that would be an *elastic collision*.

- You may hear people say that energy is not conserved in an inelastic collision. Clearly this is not true, as it would violate conservation of energy.
- What people should say is that *kinetic* energy is not conserved in the collision. While the kinetic energy is not the same before and after the collision, the TOTAL energy is conserved.
- Some of the energy is converted to heat.
- Some of the energy is converted to sound (vibrations).
- The remaining energy is in the form of kinetic energy from the motion of the new ball/bob system.
- If you had a way to measure all of the energy that is “lost” due to heat (Q) and sound (E_s), you would find that the total energy is conserved in an inelastic collision:

$$K_{ball} = Q + E_s + K_{ball+bob} \quad (6.4)$$

The kinetic energy of the ball/bob system is then:

$$K_{ball+bob} = \frac{1}{2}MV^2, \quad (6.5)$$

where M is the combined mass of the pendulum bob and the ball, and V is the velocity of the pendulum bob and ball. To determine V , we need to use conservation of angular momentum. As you probably have not encountered angular momentum yet, the result is given for you below without further explanation:

$$V = \frac{mvL}{MR}, \quad (6.6)$$

where L is the perpendicular distance from the center of the ball to the top of the pendulum truss, and R is the distance from the top of the pendulum to its center of mass. See Fig.6-2. Since the pendulum bob is at the bottom of its swing at this point, the gravitational potential energy is 0.

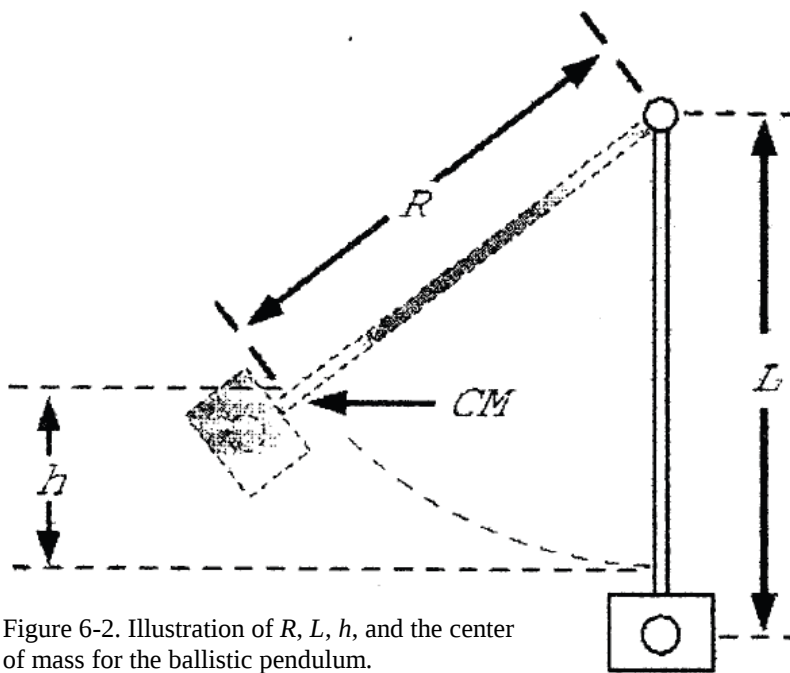


Figure 6-2. Illustration of R , L , h , and the center of mass for the ballistic pendulum.

Stage 5

In Stage 5 the pendulum bob has been stopped at the maximum height of its swing. At this point $V = 0$, and thus the pendulum bob has no kinetic energy. That means that all of the energy of the bob/ball system is gravitational kinetic energy:

$$U_g = Mgh_1 - Mgh_0 = Mgh , \quad (6.7)$$

Where h is the change in height of the pendulum bob from the bottom of its swing to the top of its swing. See Fig. 6-2.

Energy Transfer Efficiencies

The energy transfer efficiency of an event is given by:

$$\varepsilon = \frac{E_{\text{Out}}}{E_{\text{In}}} \times 100\% . \quad (6.8)$$

where E_{In} and E_{Out} are the total mechanical energy (such as kinetic and gravitational potential energy) before and after the event, respectively. The efficiency is a measure of how much mechanical energy is conserved. If the efficiency is less than 100%, that means that some mechanical energy has been converted to other forms of energy such as heat, sound, or rotation. In today's experiment you will look at the efficiency of two events:

1. The collision of the ball and pendulum bob, given by:

$$\varepsilon_{\text{collision}} = \frac{K_{\text{ball+bob}}}{K_{\text{ball}}} \times 100\% \quad (6.9)$$

2. The efficiency of the pendulum itself:

$$\varepsilon_p = \frac{U_g}{K_{\text{ball+bob}}} \times 100\% \quad (6.10)$$

Pre-Laboratory Questions

1. A 61.0-g ball traveling at 6.3 m/s is caught by a 220-g pendulum bob. The center of mass of the pendulum / ball system reaches a maximum height of 10.4 cm (relative to the initial rest position) after the collision. Calculate:
 - a. The initial kinetic energy of the ball (K_{ball}).
 - b. The gravitational potential energy of the pendulum/ball system at the end (U_g).
 - c. The kinetic energy of the pendulum/ball system in the instant after the collision ($K_{ball+bob}$). Use $L=30.2$ cm and $R=26.3$ cm.
 - d. The efficiency of the collision ($\varepsilon_{collision}$).
 - e. The efficiency of the pendulum (ε_p).

Equipment List

Beck Ball Pendulum
Ball Carrier
Digital Calipers
Safety Glasses

Insulated Glove
Logger Pro Software
Photogate (2)

EB-03 Beck Ball Pendulum

RACK ASSEMBLY

1. RACK
2. SOCKET HEAD CAP SCREW (2)
3. RACK MOUNT
4. HEXHEAD CAP SCREW (2)
5. WASHER (2)

BASE ASSEMBLY

6. BASE
7. SLOTTED HEAD SCREW (4)
8. RUBBER FOOT (4)

PENDULUM ASSEMBLY

9. PENDULUM TRUSS
10. PENDULUM BOB
11. RUBBER BAND
12. BALL TRAP PLATE (3)
13. PIN (5)
14. PAWL

PENDULUM SUPPORT ASSEMBLY

15. KNURLED NUT
16. PENDULUM MOUNTING SCREW
17. SOCKET HEAD CAP SCREW
18. BEARING (2)
19. SHAFT
20. SHAFT HOUSING
21. MAST
22. HEXHEAD CAP SCREW (3)
23. WASHER (3)

GUN ASSEMBLY

24. HEXHEAD CAP SCREW (3)
25. WASHER (3)
26. TRIGGER RETURN SPRING
27. SOCKET HEAD SETSCREW
28. SOCKET HEAD CAP SCREW (4)
29. FACE PLATE
30. TRIGGER
31. STEEL WASHER
32. TEFLON WASHER
33. RAM
34. SPRING
35. GUIDE ROD
36. WASHER
37. SOCKET HEAD CAP SCREW
38. TRIGGER STOP
39. GUN HOUSING

BALL STORAGE

40. STAINLESS STEEL BALL
41. BALL STORAGE UNIT
42. NUT
43. WASHER
44. LOADING PLATE

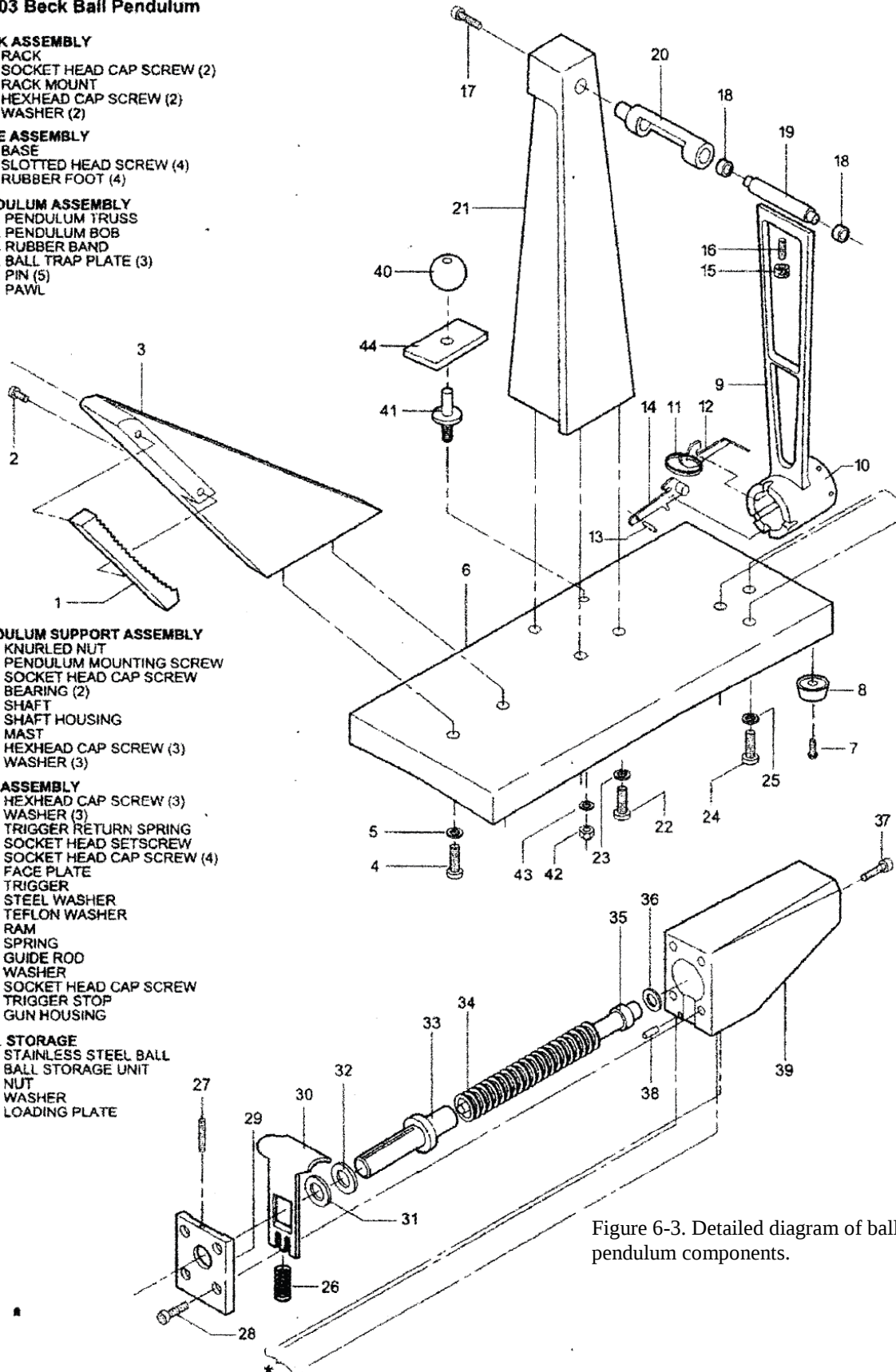


Figure 6-3. Detailed diagram of ballistic pendulum components.

Experimental Procedure

Safety Warning

The ballistic pendulum launches a heavy ball at high velocity.
You **MUST** wear eye protection at all times.

Part I: Initial Measurements

A detailed diagram of all components of the ballistic pendulum is shown in Fig. 6-3. This procedure will refer to various parts of the pendulum using the numbers in Fig. 6-3. Example: “The rack (1) is attached to the rack mount (3) using socket head cap screws (2).”

Before using the ballistic pendulum, you must make a few initial measurements:

- Remove the pendulum truss (9) from the pendulum support by unscrewing the knurled nut (15).
- Use the balance in the back of the room to determine:
 - The mass of the ball, m
 - The combined mass of the pendulum and ball, M .
- The center of mass for the combined pendulum and ball system should be marked with a black line on the pendulum truss (9) relatively close to the pendulum bob (10). See Fig. 6-4. You will use this mark when measuring the distance from the top of the pendulum to the center of mass.
- If it is not marked, or you believe that it is not marked correctly, you can determine the center of mass yourself with the following procedure. **Note that you do not have to do this yourself if the pendulum is already marked.**
 - Place the ball in the pendulum bob.
 - Balance the pendulum on the edge of a meter stick, or some other item that resembles a knife-edge.
 - The balancing point is the center of mass. Mark it with a **pencil**, *not* a pen or permanent marker. (Permanent marking of the center of mass is to be done by laboratory staff only.)

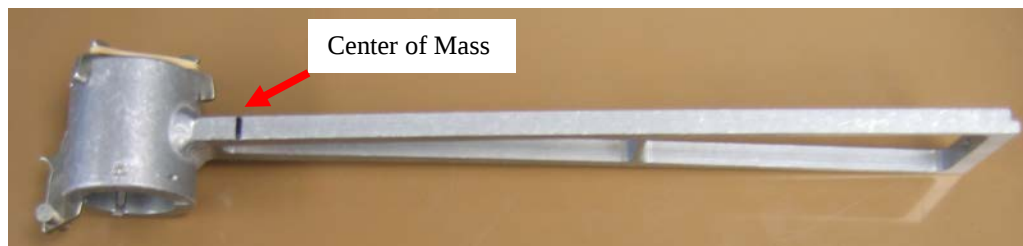


Figure 6-4. Center of mass marking on pendulum truss.

- Return the pendulum truss (9) to the pendulum support, making sure to tighten the knurled nut (15).

- Measure L , the perpendicular distance from the center of the ball to the center of the shaft (19). See Figure 6-2.
- Measure R , is the distance from the center of mass marking to the center of the shaft (19). See Fig. 6-2.

Part II: Velocity and Kinetic Energy

In order to determine the kinetic energy of the flying ball (Stage 3 from the introductory material), you will have to measure the velocity of the ball. You will measure this velocity using two photogates.

- You will not be firing the ball into the pendulum bob until Part III. For now, push the pendulum bob up until the pawl (14) catches in the rack (1). See Fig. 6-5.
- Examine the dual photogate assembly. If needed, adjust the alignment and position of the photogates so that:
 - Both photogates are similarly aligned.
 - The top of the photogates touch.

See Fig. 6-6 for proper photogate alignment and position.

- Move the photogate assembly so that it just rests against the mast (21). See Fig. 6-5 and 6-6.
- Plug the photogates into the LabPro (or LabQuest Mini) making sure that photogate 1 (the first photogate that the ball will pass through after being fired) is plugged into the DIG/SONIC 1 port and that photogate 2 is plugged into the DIG/SONIC 2 port.
- Start LoggerPro and open “Exp M5 – Ballistic Pendulum”(Note that this experiment makes use of a LoggerPro template for a similar experiment originally done in a different course, hence M5 instead of A6).
- The height of the photogates must be adjusted so that they are blocked when the ball flies through them. Using the ball carrier (which is approximately at the same height as the ball when fired), adjust the height of the photogates so that the red lights on top of the



Figure 6-5. Setup for Part II. Note that the pendulum bob is up on the rack and that the glove is propped open ready to catch the ball after it goes through the photogates.



Figure 6-6. Alignment and positioning of photogates. They are similarly aligned and the tops touch.

photogates turn on when you pass the ball through the gates. Make sure that the light turns on for both photogates. See Fig. 6-7.



Figure 6-7. Using the ball carrier to adjust the height of the photogates.

Left: Photogate 1 is at the correct height because the red light turns on as the ball passes through.

Right: Photogate 1 is not at the correct height because the red light does not turn on as the ball passes through.

- LoggerPro will measure the time of flight between photogate 1 and photogate 2, but in order to properly calculate the ball's velocity, LoggerPro must know the distance Δx between the photogates. See Fig. 6-6. Use the digital calipers to measure Δx . Note that Δx is the distance between the “eyes” and **not** just the space between the plastic housings of the photogates.
- In LoggerPro, double-click the top of the “Velocity” column to open the column options dialog box. Change the “0.035” in the Equation box to your measured value of Δx in meters. See Fig. 6-8.
- Position the glove so that it will catch the ball after it passes through the photogates. The glove will stay in place if you put it between the rack (1) and the base (6). See Fig. 6-5. Make sure the wrist of the glove is open so that it can catch the ball. Never fire the gun if the bob is up and the glove is not in place.
- Cock the gun by placing the cylindrical loading block over the guide rod (35) and push until trigger clicks into place. Note that you will have to move the photogate assembly out of the way every time you load the gun. Be careful not to change the height or alignment of the photogates when moving the assembly.

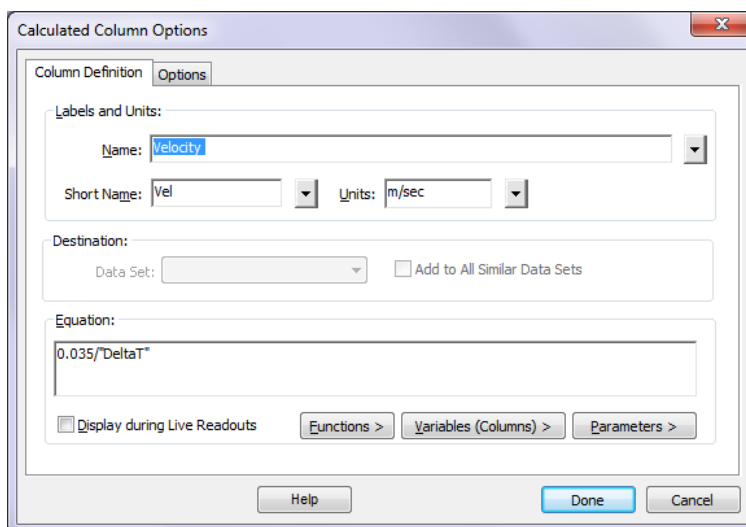


Figure 6-8. Column Options dialog box for “Velocity” column.

- The gun can be cocked in three different positions, but you will only use the first of these positions for this experiment. If at any point in either Part II or later in Part III you think that you may have used the second or third position, throw out that data point and do another trial making sure that the gun is cocked in the first position.
- Put the ball over the guide rod (35) and slide it all the way back towards the face plate.
- Put the photogate assembly back in place.
- In Logger Pro, hit collect.
- Fire the gun by pressing down on the trigger (30) with a firm even pressure.
- If everything was properly aligned, there should now be one row of data in LoggerPro, and the ball should be in the glove.
- Remove the ball from the glove and repeat the above procedure four more times so that you have five different values for the velocity of the ball. If LoggerPro stops collecting data before you finish all trials, record the velocities you do have, hit collect again and finish the rest of your trials.
- If the velocity of any trial is significantly different from the other values, make sure that:
 - The photogates are still properly aligned and at the right height.
 - The gun is cocked in the first position (and not the second or third).
 - That nothing other than the ball went through either photogate while data was being collected. (For example, when you moved the photogate assembly between trials, did your hand block the gates?)If you suspect that any of the above is true, repeat the trial.
- Calculate the average velocity, $\langle v \rangle$. Show your work in a SAMPLE CALCULATION.
- Calculate the kinetic energy of the ball, K_{ball} . Show your work in a SAMPLE CALCULATION.
- Remove the photogate assembly from the ballistic pendulum and exit Logger Pro, as you will not use them in Part III.

Part III: Inelastic Collision and Conversion of Kinetic Energy to Gravitational Potential Energy

In this part you will go through all five stages of the ballistic pendulum's operation as described in the Introductory Material.

Stage 1

- Cock and load the gun in the first position as you did in Part II.
- Potential energy is being stored in the gun's spring.

Stage 2

- Release the pendulum bob (10) from the rack (1) so that it hangs vertically. Make sure that the pendulum is not swinging.
- Fire the gun as you did in Part II.
- Potential energy stored in the spring is being converted to kinetic energy.

Stage 3

- The ball flies towards the pendulum bob with kinetic energy K_{ball} which you already calculated in Part II.

Stage 4

- The ball is caught by the pendulum bob in an inelastic collision. Some of the ball's kinetic energy is converted to the kinetic energy of the ball/bob system, $K_{ball+bob}$.
- Calculate $K_{ball+bob}$ using Eqs. 6.5 and 6.6 and your measurements from Part I and Part II. Show your work in a SAMPLE CALCULATION.

Note: Even though you will do multiple trials, you only have to calculate $K_{ball+bob}$ once.

Stage 5

- The kinetic energy of the ball/bob system is converted to gravitational potential energy.
- When the ball reaches its maximum height, the pawl (14) under the pendulum bob (10) is caught in one of the notches on the rack (1). See Fig. 6-9.
- Record the notch #.
- At this point all of the remaining energy in the system is in the form of gravitational potential energy, see Eq. 6.7
- Remove the ball from the pendulum bob by pushing outward on the ball trap plates (12) which are pulled towards each other with rubber bands.
- Fire the gun 7 more times, recording the notch # each time. Check to make sure the nut at the top of the pendulum is tight each time you fire the gun. If the nut is loose, the pendulum bob may not catch in the rack.
- Calculate the average notch #.
- Now we will determine h in Eq. 6.7.
 - Release the pendulum bob so that it is hanging vertically. Measure the height of the center of mass marking from the base. This is h_0 .



Figure 6-9. Pendulum bob caught by rack after the ballistic pendulum is fired. In this picture the pawl is caught in notch #18.

- o Round the average notch # to the nearest whole number. Swing the pendulum upward and let the pawl rest in that notch. Again measure the height of the center of mass marking from the base. This is h_1 .
- Determine the gravitational potential energy from Eq. 6.7.

Part IV: Clean Up

- Put the ball back on the ball storage unit (41).
- Tidy the lab bench.
- Exit any running software, but do not shut down the computer.

Sample Calculations Summary

Page A6-11: $\langle v \rangle$

Page A6-11: K_{ball}

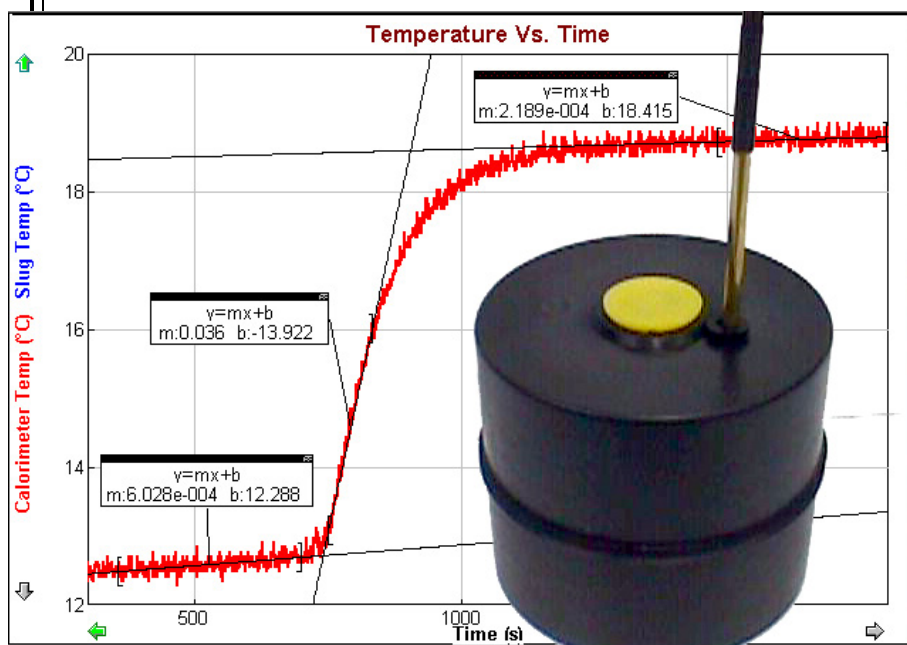
Page A6-12: $K_{ball+bob}$

Analysis Questions

1. Calculate the efficiency of the collision, $\varepsilon_{collision}$. If kinetic energy is conserved in a collision, then the collision is said to be elastic. If kinetic energy is not conserved, then the collision is said to be inelastic. What type of collision occurred between the ball and the pendulum bob?)? If the collision was inelastic, where, **during the collision**, did the lost mechanical energy go? Be as specific as possible.
2. Calculate the efficiency of the pendulum, ε_p . Here you should notice that energy is essentially conserved ($\varepsilon_p > 70\%$). Of course a real pendulum is not an ideal pendulum, and some energy is lost. Where did the rest of the energy go?

EXPERIMENT A8:

Specific Heat



Objectives:

- Measure the specific heat of brass.
- Measure the specific heat of an unknown metal sample.
- Learn about calorimetry as a method of measuring heat.
- Learn to use asymptotic lines to find the “elbow” in a curve.

Introductory Material

The specific heat C of a material is defined as the amount of heat energy required raise the temperature of a specified amount of that material by 1°C . We are going to determine the specific heat of a sample (not necessarily chemically pure) by observing the rise in the temperature of a container when the hot sample is added to it.

Our method is simple. We will use a measurement instrument called a “calorimeter,” which is really nothing more than an aluminum can in an insulating jacket. The aluminum can in the calorimeter has an initial temperature T_0 . We will then take a metal sample, heat it to a temperature T_s , and drop it into the aluminum can. The aluminum can will then heat up while the sample cools down. Eventually they will both reach a final temperature T_f . T_f will be between T_0 and T_s , as sketched in Figure 8.1. You will measure these temperatures and use them to calculate the specific heat C_s of the metal sample.

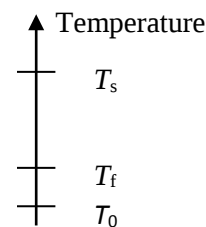


Figure 8.1

We will use the following notation:

	Mass	Specific heat	Temperature initial	Temperature final
sample	M_s	C_s	T_s	T_f
calorimeter	M_c	C_c	T_0	T_f

The calorimeter is made of aluminum, which has a specific heat $C_c = 900 \text{ J/kg}^\circ\text{C}$.

Conservation of energy requires that any heat energy lost by the metal sample must go somewhere. We will assume that all of this energy is absorbed by the calorimeter. Making this assumption, we have:

$$\text{heat lost by sample} = \text{heat gained by calorimeter}$$

which we can write as:

$$M_s C_s (T_s - T_f) = M_c C_c (T_f - T_0). \quad (8.1)$$

By measuring T_s , T_f , and T_0 , and knowing M_s , M_c , and C_c , it is possible to calculate the unknown specific heat of the sample, C_s .

Relative to room temperature,

$$\text{Initial total energy} \quad M_s C_s (T_s - T_{\text{room}}) + M_c C_c (T_0 - T_{\text{room}}) \quad (8.2)$$

$$\text{Final total energy} \quad M_s C_s (T_f - T_{\text{room}}) + M_c C_c (T_f - T_{\text{room}}) \quad (8.3)$$

By assuming that all of the energy released by the hot sample is absorbed by the calorimeter, we have neglected any other loss of heat.

In fact, some heat is lost by three mechanisms: radiation, conduction, and convection. These can potentially be significant sources of error. To reduce these losses, the calorimeter has the following features:

- the aluminum can is suspended in styrofoam, which has a low thermal conductivity
- the cover of the container inhibits transfer of heat to the outside air.

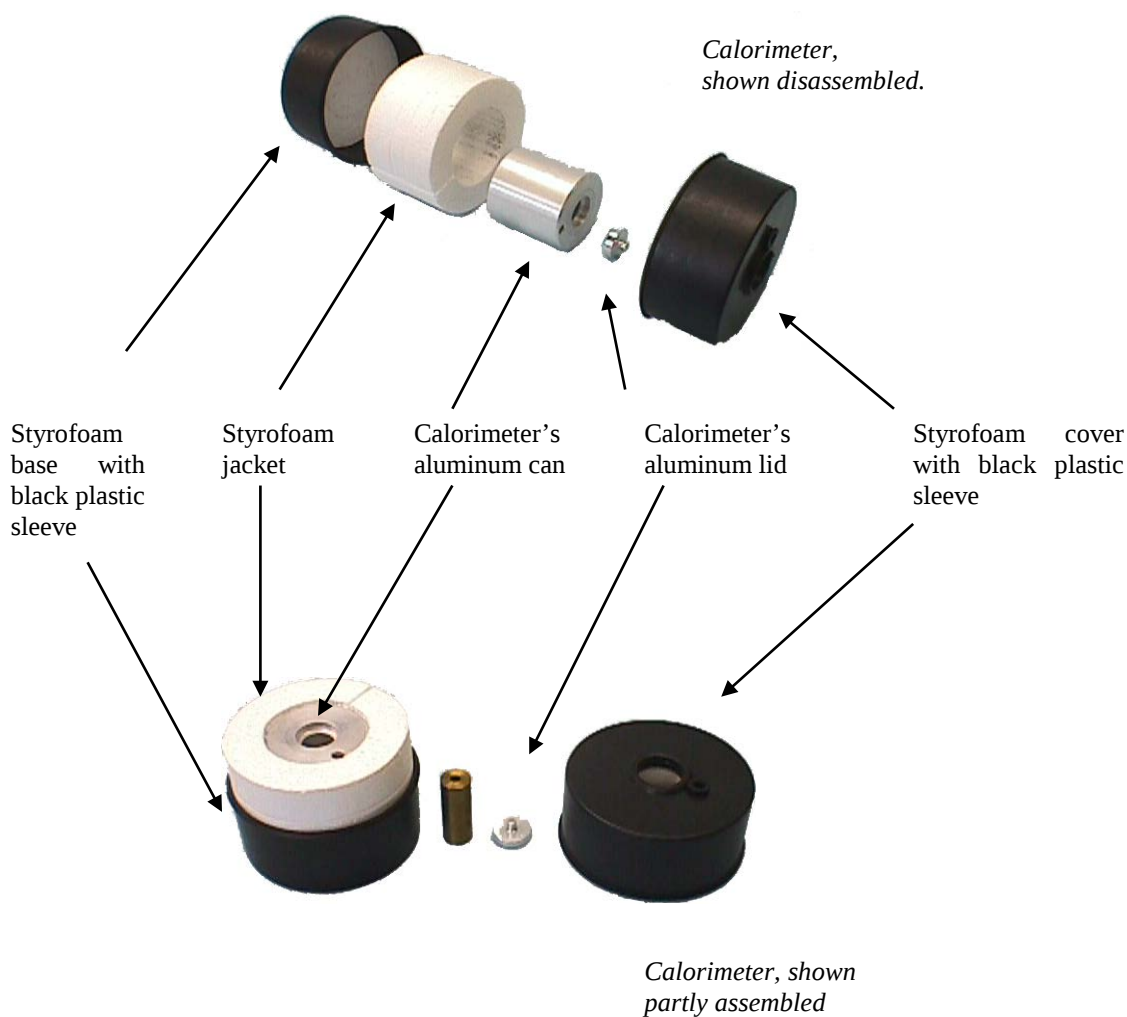


Figure 8.2

A table of the specific heats of several materials is listed below:

Material	Specific Heat C (J / kg °C)
Water	4184
Beryllium	1825
Wood	1400
Aluminum	900
Glass	753
Silicon	705
Stainless Steel	502
Copper	386
Brass	381
Germanium	320
Silver	235
Gold	129
Lead	129

Pre-Laboratory Questions

1. Suppose that after you measure the specific heat C_s of the brass sample, you repeated your measurements with another brass sample, of twice the mass. What result would you expect, and why?
2. Look at the table above. If you had two samples of the same mass, one wood, and the other silver, which would require more heat to increase the temperature by 10 °C? Explain.

Equipment List

Calorimeter	Temperature probe * (2)
Brass Sample	Computer*
Hot plate	Logger Pro software
Insulated Glove	Forceps
1000 mL Beaker (for ice)	Unknown Metal Sample

* An asterisk indicates that an item is described in the Instrument Glossary.

Safety Warnings

- You will use a hot plate with an exposed heater.

Do not burn yourself.

Do not allow combustible material to touch the hot plate.

Do not allow the probe wires to touch the hot plate.

Do not heat the sample hotter than 80° C.

- You will use ice from a machine that has not been cleaned.

Do not eat the ice.

Experimental Procedure

The most critical measurement in this experiment is the determination of the rise of the temperature of the calorimeter, $T_f - T_0$. This rise does not occur instantaneously and so we must plot the temperature as a function of time to determine an appropriate $T_f - T_0$.

Logger Pro will be used throughout this experiment to record the temperature as a function of time.

Part I: The Specific Heat of Brass



1. Measure the mass M_s of the sample, i.e., the brass cylinder.
2. Measure the mass M_c of the calorimeter's aluminum can and its aluminum lid.
3. Turn on the hotplate to between the #1 and #2 settings.
4. Plug the temperature probes #1 and #2 into CH1 and CH2 of the LabPro device. Make sure the LabPro device is plugged into the computer and start LoggerPro.
5. Open the template "Exp. H3 - Specific Heat" (Note that the "H3" is correct; this experiment makes use of the same template file as a more challenging specific heat lab that is done by more advanced classes).
6. Insert temperature probe #2 into the brass sample. Place the brass sample directly on the hot plate as shown in the right picture of Figure 8.3 (**Do not fasten the probe to the clamp!** Just set the probe on top of the clamp). Set the hot plate to 130 degrees in order to heat the sample quickly. To increase the temperature of the hot plate, simply turn the knob clockwise. When choosing a temperature setpoint, the display will indicate the chosen setpoint for 5 seconds, after which the display will flash until the setpoint temperature is reached. Move on to step 7, but pay attention to the temperature of the brass. In order to prevent overheating the sample, turn the hot plate down to about 90-100 degrees when the sample reaches about 55 °C.
7. Fill a plastic 1000 mL beaker with ≈ 400 mL of ice and water. Place the calorimeter and its lid in the ice water as shown in Figure 8.3.
8. Insert temperature probe #1 into the calorimeter. The temperature of the calorimeter will need to be about 8 degree below room temperature. If it is significantly higher or lower than that, add a little ice or water.



Figure 8.3.

Left: Chilling the calorimeter in ice water.

Right: Heating the sample on the hot plate. The temperature probe is inserted into the sample, both as a handle and to record the temperature of the sample. The clamp is used to support the temperature probe. Notice that the probe merely rests on top of the clamp. Do not actually fasten the probe in the clamp!

9. Once the calorimeter has been cooled to about 8 degrees below room temperature, take it out of the ice water slurry and dry it off. Make sure it is **completely dry**. This includes the small temperature probe hole and the hole where the lid goes.
10. Once you have **completely dried** the calorimeter (inside and out), reassemble it into the styrofoam jacket as in Figure 8.2. After installing the cover, insert temperature probe #1 into the calorimeter, and click the  Collect button on logger pro.
11. Keep heating the brass sample to approximately 60 - 80° C. **Do not heat it above 80° C.**
12. After the probe has rested in the calorimeter for about 3 min, the temperature will stabilize and increase slightly. Wait 5 more minutes so that the slightly increasing temperature region continues for at least 300 seconds.



Figure 8.4. Forceps holding the calorimeter lid.

13. Once the brass sample temperature is about 60 - 80° C, remove the hot brass sample from the heater. The following steps (illustrated in Figure 8.5) must now be completed without wasting any time between steps:

- (a) Tilting the calorimeter as shown in the photo, insert it in the calorimeter.
- (b) Reinstall the calorimeter lid
- (c) Reinstall the calorimeter's plastic cover.

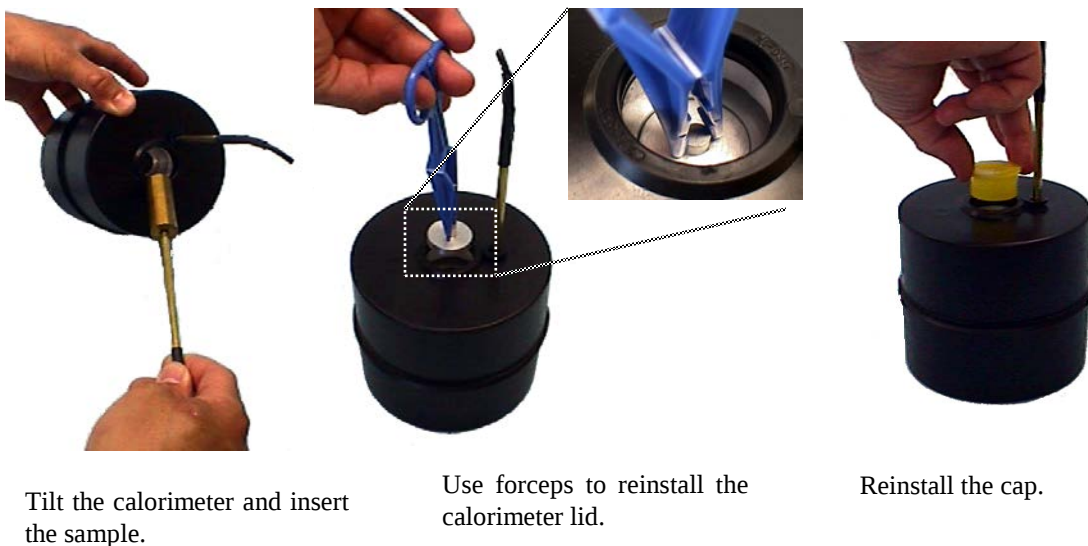


Figure 8.5. Installing the sample in the calorimeter.

14. Turn off and unplug the hotplate.

- 15. Wait until the temperature has stabilized (*at least* 10 minutes, longer if necessary) and you have enough data to make linear fits as in Figure 8.7. Press the “Stop” button on Logger Pro.
- 16. Double click the maximum number on the temperature axis and change the “Top” value to 100 so that you can see both probe temperatures completely.
- 17. There should be a sharp bend in the data for the brass sample’s temperature probe when you dropped the brass sample into the calorimeter, exposing the temperature probe to the cool air. This is the temperature T_s (the sample temperature just before you put it into the calorimeter). Press the “Examine” button  to read temperature T_s .
- 18. Change the maximum numbers on the temperature axis to 20 so that you can see the Probe #1 graph only, as shown in Figure 8.7.

You will now find the temperatures T_0 and T_f for the calorimeter. If the calorimeter responded instantaneously, your data would like Figure 3.8. However, due to the finite time response of the calorimeter, identifying T_0 and T_f is more complicated. The temperature vs. time curve has two

“elbows,” and we would like to measure our plot to identify a point where we can say, “The elbow is at this exact point.” We will use a very common method of identifying the elbow on a curve which involves finding “asymptotic lines” that fit the data in your plot.

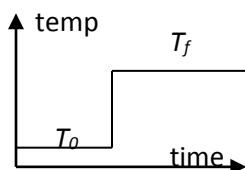


Figure 8.6.

If the calorimeter temperature responded instantaneously, your plot would look like this.

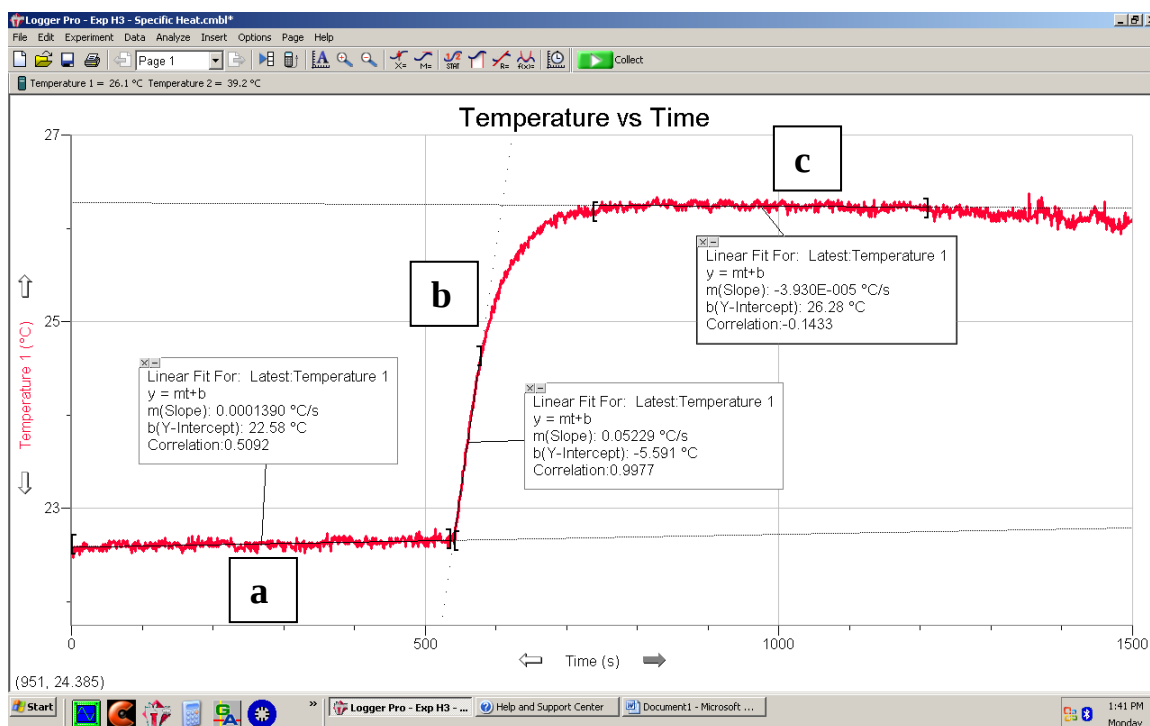


Figure 8.7. Typical data for probe #1.

- You will use Logger Pro to fit the data and draw three “asymptotic” lines, as shown here.
- The intersections of lines (a) and (b) yields T_0 , as shown with the lower dotted line.
- The intersections of lines (b) and (c) yields T_f , as shown with the upper dotted line.

The asymptotic lines, shown in Figure 8.7, mimic the straight lines in Figure 8.6:

- ☐ Asymptotic line (a) would ideally be horizontal, but it probably slopes upward.
 - ☐ Asymptotic line (c) would also be horizontal, ideally. It might slope downward or upward.
 - ☐ Although the section between asymptotic lines (a) and (c) is a curve, the first 33% of this curve can be fit by a straight line.
 - ☐ You will examine why this graph deviates from the ideal of Figure 8.6 in the analysis questions.
-
- Use your mouse to select data *before* the temperature began to increase. The data should probably be ≥ 30 sec in length. Use Logger Pro's linear regression button to fit the data to a line. This yields asymptotic line (a).
 - Repeat for asymptotic line (b). In selecting the data to fit, choose approximately the first 33% of the temperature rise.
 - Repeat for asymptotic line (c). In selecting the data to fit, choose the last few hundred seconds of data.
 - Move the three text boxes with the fit results so that you can read all three.
 - Print a copy of the graph for each partner. Label lines (a), (b), and (c) on the graph. You will use this graph in the analysis questions.
 - You can find the temperatures T_0 and T_f by solving for the intersection (x, y) of two straight lines. If you have lines $y = m_1x + b_1$ and $y = m_2x + b_2$, with some basic algebra it can be shown that the y coordinate of the intersection is given by $y = \frac{m_1b_2 - m_2b_1}{m_1 - m_2}$
 - o Calculate T_0 using the intersection of lines (a) and (b).
 - o Calculate T_f using the intersection of lines (b) and (c).
 - C_s , the specific heat of brass can be calculated by solving Equation 8.1 for C_s . The result is $C_s = \frac{M_c C_c (T_f - T_0)}{M_s (T_s - T_f)}$. Show your work in a SAMPLE CALCULATION.
 - Calculate the % error between your measured value of C_s and the expected value of C_s for brass.

Part II: The Specific Heat of an Unknown Metal Sample

Repeat the procedure from Part I to find the specific heat of the unknown metal sample, but start with the hot plate set to 150 degrees this time. Use the table of specific heats in the introductory material to identify the sample.

Part IV: Clean Up

- Verify that the hot plate is turned off.
- Remove the sample from the calorimeter.
- Empty any water containers.
- Dry any spills.
- Exit Logger Pro. Be sure *not* to save any files when asked by Logger Pro.
- Tidy the lab bench.

Sample Calculations Summary

Part I: The Specific Heat of Brass

Page A8-10: C_s

Part II: The Specific Heat of an Unknown Metal Sample

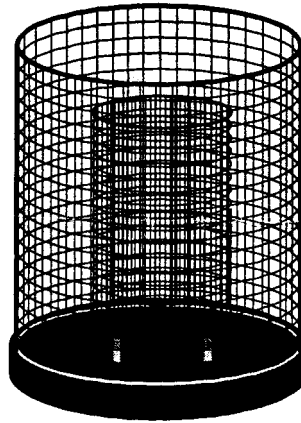
Page A8-10: C_s

Analysis Questions

1. If you look at your graph from Part I, you will notice that it deviates from the ideal case shown in Figure 8.6.
 - a. Why does line (a) slope upward?
 - b. Why is line (b) not a vertical line?

EXPERIMENT A9:

Charge Measurement



Faraday ice pail

Objectives:

- *Scientific:* Observe triboelectric charging.
- *Scientific:* Learn about Faraday ice pails for measuring charge.
- *Skill development:* Learn about grounding.

Introductory Material

This experiment has two unrelated topics. In Part I, you will measure charges, while in Part II you will develop skills with log-log plots that you will use again later in this course.

In Part I you will measure the charge on some objects. You will apply the charge to these objects by triboelectric charging, which means a transfer of charge by rubbing two dissimilar objects. What happens in triboelectric charging is that electrons come off one surface and are transferred to the other. The charge on an electron is small

$$q_e = 1.6 \times 10^{-19} \text{ Coulomb}$$

which means that developing a significant charge requires the transfer of many electrons.

Some materials release electrons more easily than others. For example, rubbing wool on a polymer, you will find that the polymer charges negatively, which tells you that wool gives up electrons more readily than polymer.

You are familiar with triboelectric charging already: for example, if you walk across a carpet and touch a doorknob, you get a shock due to the rubbing of your shoes on the carpet. This effect is strongest in winter, when the air is dry. During the summer the moisture in the air conducts electricity, and objects do not retain their charge as long.

“Ground” is a term used both as a noun and a verb.

noun: A ground is a large conducting object that is at the potential we define to be zero volts. In a building, good grounds are:

- ❑ a pipe stuck deep into the ground.
- ❑ water pipes and gas pipes
- ❑ the third wire in an electrical outlet.

verb: When you *connect* something to ground, it is said that you have *grounded* it.

Your body is an object that must sometimes be grounded, to eliminate its electrostatic charge.

The instruments you will use to measure charge are a Faraday ice pail and an electrometer:

- The concept of a *Faraday ice pail* will be developed later in the lecture part of this course. For now, we'll give you just a basic idea of how it works, as sketched in Figure 9-1. A charge placed inside a conducting surface induces an equal charge on the outside of that surface. The Faraday ice pail is a set of two concentric metal screen

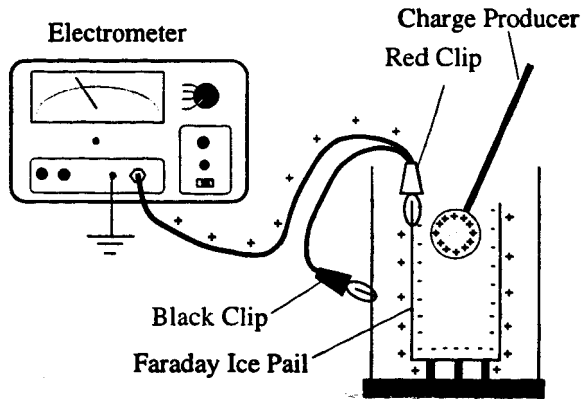


Figure 9-1. Faraday pail concept. The charged object, in this case the “Charge Producer,” induces a charge on the inner cylinder. The electrometer measures a voltage that corresponds to that charge.

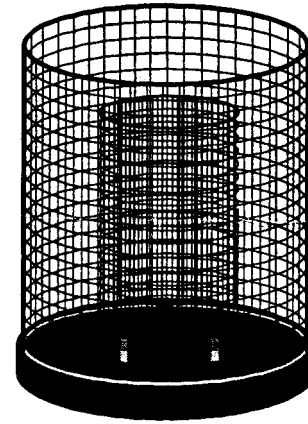


Figure 9-2. Faraday ice pail

cages, as shown in Figure 9-2. When you put a charged object inside the inner cage, an electric potential V appears across the two cages. You can measure this potential with an electrometer.

- An *electrometer* is a kind of voltmeter. Compared to ordinary voltmeters, it has a particularly high input impedance of $10^{14} \Omega$. The concept of impedance will be developed later in this course; for now, it is enough to know that this instrument’s high input impedance allows a measurement without disturbing the charge of the object that you measure. The front panel of this instrument is shown in Figure 9-3.

The charge Q of the object is proportional to the voltage or potential V , that you will measure on the electrometer:

$$Q = CV \quad (9.1)$$

where the proportionality constant is the capacitance C , which has units of Farads (F). The units are related by $1 \text{ Coulomb} = 1 \text{ Farad} \times 1 \text{ Volt}$. You will learn more about the concept of capacitance later in this course. For now, it is enough to know that the capacitance of the system (including the Faraday ice pail, the test probe, and the electrometer) is approximately $C = 150 \text{ pF}$ (where $p = \text{pico}$ indicates 10^{-12} and $F = \text{Farads}$).

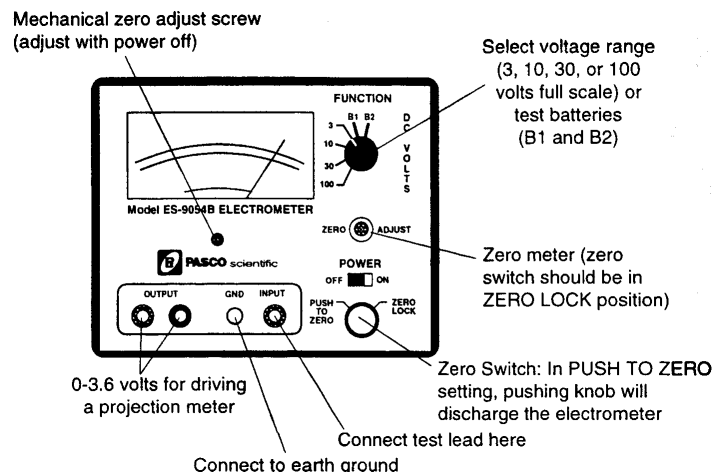


Figure 9-3. Electrometer front panel.

Pre-Laboratory Questions

1. Suppose you rub an object and it acquires a charge of 10^{-8} C. How many electrons were rubbed off of it?
2. Explain why it is important to ground both yourself and the equipment between making charge measurements in this experiment.

How to dress for this lab

- Don't wear wool or synthetic materials such as nylon. This helps to avoid disturbing your experiment with an electrostatic charge.
- Cotton and cotton-blend clothes are ideal.

Equipment List

- * Faraday Ice Pail
- * Electrometer
- Cable for Faraday Ice Pail (one end BNC, the other end two alligator clips)
- Set of blue and white charge producers
- Two proof planes
- Two conducting spheres
- * Banana plug cable, approx. 60 cm
- * Alligator clip
- Materials: glass rod (pyrex is best), ebonite rod, PVC pipe, silk cloth, neoprene rubber glove, wool cloth.

* indicates that an item is described in the Instrument Glossary.

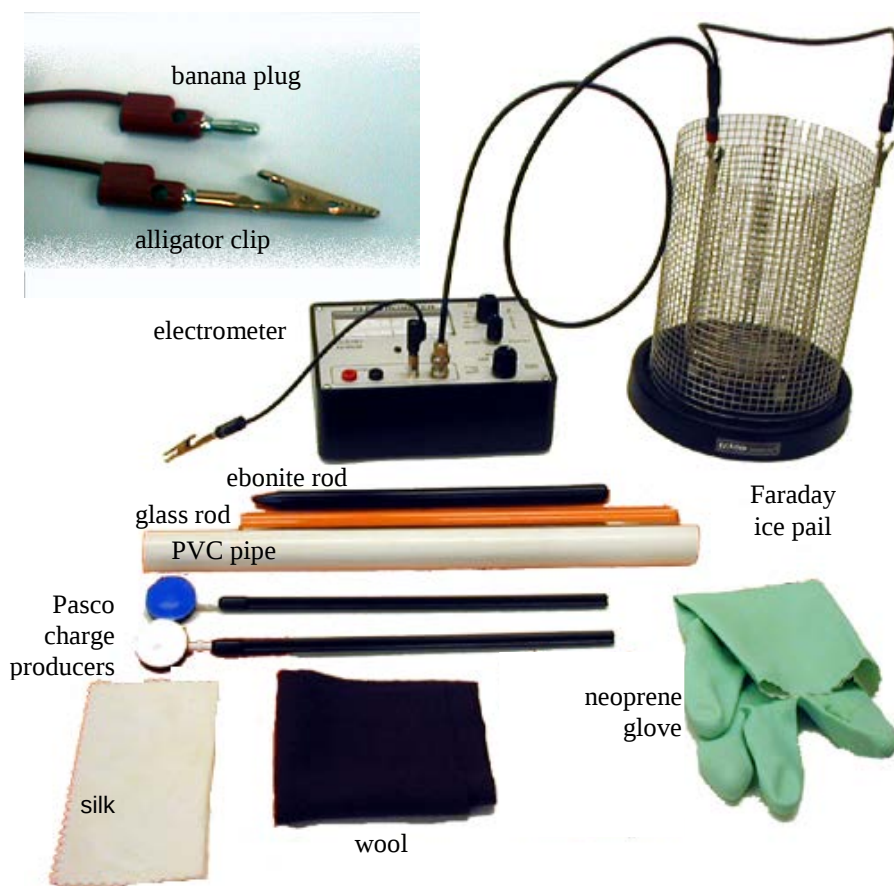


Figure 9-4. Setup. You will find it convenient to put your entire setup near an air nozzle or gas nozzle.

Experimental Procedure

Part I: Triboelectric Charging

The goal of Part I is to observe that rubbing objects together produces a charge, and that the charge can be either positive or negative.

This experiment is not well suited for *quantitative* measurements. The difficulty is that we will transfer charge from one place to another, and sometimes charge gets lost or transferred in unexpected ways. Therefore, you are encouraged not to take the quantitative values that you measure too seriously. More important is that you learn:

- ❑ rubbing causes a transfer of charge,
- ❑ the charge can be positive or negative, depending on the two materials that are rubbed.

Set the apparatus up:

- Connect the leads of the test probe to the Faraday ice pail, as shown in Figure 9-5.
- Connect the ground cables as shown in Figure 9-6.
- Adjust the zero of the electrometer as shown in Figure 9-7. Hold down the “PUSH TO ZERO” button, and turn the “ZERO ADJUST” knob until the needle points to zero.

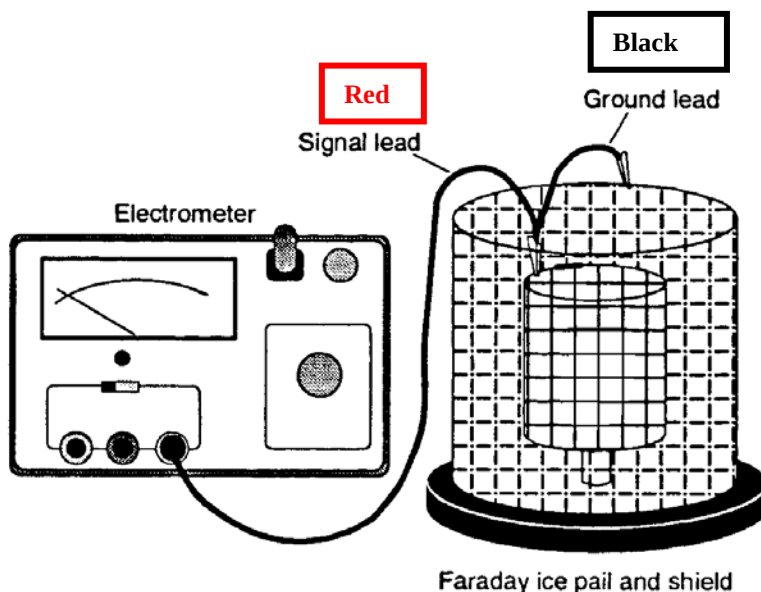


Figure 9-5. Connecting the electrometer and the Faraday ice pail.

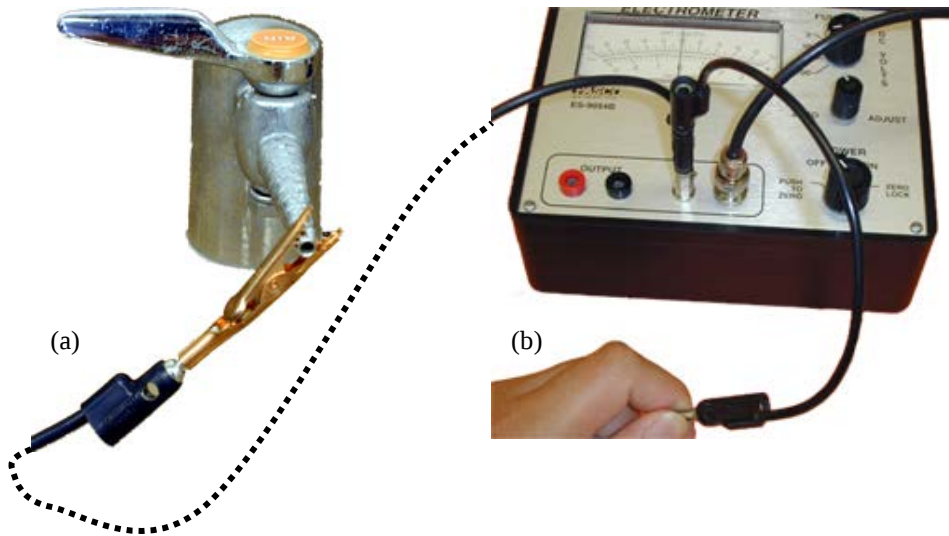


Figure 9-6. Grounding.

(a) Attach an alligator clip to an Earth ground, like an air nozzle.
(b) The other end of the cable is connected to the GND connector of the electrometer. Stack a second banana plug connector on top of the electrometer's GND terminal – that will allow you to hold a grounded banana plug while performing the experiment to ground your body.



Figure 9-7. To zero the electrometer, hold down the “PUSH TO ZERO” button while turning the “ZERO ADJUST” knob, until the needle points to 0. Use the top scale for reading using the “10” or “100” scales (multiply your reading by 10 if on the “100” scale) and the bottom scale for the “3” or “30” scales (multiply your reading by 10 if on the “30” scale).

Procedure to ground yourself, the electrometer, and the Faraday ice pail:

- Connect the GND terminal on the electrometer to a ground. One way to do this is to use a lead with banana plugs, and connect one end to a gas or air nozzle using an alligator clip, as shown in Figure 9-6 (a).
- At your lab station, ground yourself by holding a banana plug at the end of a cable attached to an Earth ground, as shown in Figure 9-7 (b).

The Faraday ice pail is not connected to any Earth ground, such as the third wire in an electrical outlet. Instead, it is “floating,” which means that it is not connected to other conductors. In this case, to ground the ice pail, there are two methods. You can try both:

1. Touch your finger to both the inner and outer cylinders. Be sure that when removing your finger, you remove it from the inner cylinder first and the outer cylinder second, as shown in Figure 9-8.
2. Alternatively, push the “zero” button on the electrometer. This is a momentary-contact switch that shorts the electrometer’s two input leads, thereby removing the charge on any object, such as the Faraday ice pail, that might be connected between the two leads. See Figure 9-9.

IMPORTANT: *You should ground the Faraday ice pail before inserting a charged object, so that you can measure its charge.*

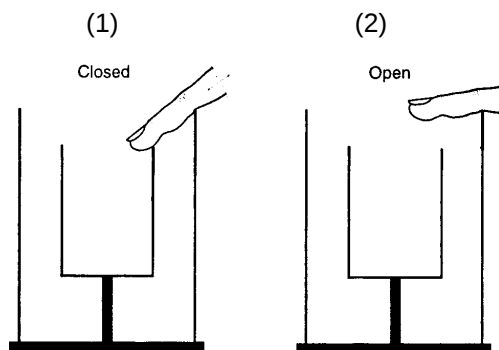


Figure 9-8. One of two methods to ground the Faraday ice pail:

- (1) touch both cylinders with a finger,
- (2) release the inner, then
- (3) remove your finger entirely.



Figure 9-9. The other method to ground the Faraday ice pail: press the “PUSH TO ZERO” button on the electrometer.

Procedure:

- Ground your body by holding onto a banana plug cable, as shown in Figure 9-6 (b) before you start the procedure.
 1. Breathe on the exposed blue and white plastic disks on the two charge producers. The moisture in your breath will remove any residual charge from them.¹
 2. Rub the blue and white charge producers together, to create a charge on them.
 3. Insert one of the wands into the lower half of the inner cylinder of the pail, but do not let it touch the pail.
 4. Set the electrometer on an appropriate scale, and record the reading (see Figure 9-7 for instructions on how to take readings for various scales).
 5. Remove the wand.
 6. Ground the ice pail.
 7. Now the other wand: Without having done anything that would disturb the charge on the other wand (i.e., touching, grounding or breathing on it), insert it and then record the electrometer reading.

Note: The charges will dissipate quickly, especially in high humidity. If you are doing this experiment during the summer term or early in the fall semester, you will need to do steps 2 through 7 quickly, or you may not measure any charge on the second wand.

¹ Consider why triboelectric charging from walking on a carpet is less noticeable in the summer than the winter. In the summer, there is more moisture in the air, and it helps remove charges from objects. Here you are exploiting the same effect to purposefully remove charge from an object.

- You are provided with several other materials. Choose a rod and a cloth/sheet (some suggestions are given below). As before:
 - Ground your body
 - Ground the electrometer
 - Breathe on the materials
 - Rub them. It works best if you rub only the free end of a rod, and not its entire length.
 - Insert the rod into the ice pail
 - Set the electrometer on an appropriate scale and record its reading. *(There's no great significance to the exact numerical value for this measurement; here we are mainly attempting to observe the effect of charging and its polarity, rather than making a precise measurement.)*

- Here is a list of some combinations of materials²:
 - Silk cloth & glass rod: *The glass charges positively when rubbed by silk.*
 - Neoprene & PVC: *PVC charges negatively when rubbed by rubber.*
 - Wool cloth & ebonite: *Polymers charge negatively when rubbed by wool.*

(The silk cloth is black, the neoprene is the green glove, the PVC is the tube, the wool cloth is purple, and the ebonite rod is black.)

- Using Eq. (1.1), compute the charge on the objects. SHOW YOUR WORK in a sample calculation.

² If you have a comb or brush, you can use it in your hair and then measure its charge. Your hair generates a much larger charge if you have not used a cream-rinse conditioner or similar product.

Part II: Charging by Induction

Charging by induction is a process where the charge that happens to already be on a conductor's surface is redistributed. This happens when a charged body, usually an insulator, is brought near the conductor. Unlike triboelectric charging, this process involves no transfer of charge from one body to another; it merely results in a redistribution of the charge that's already on the conductor. The redistribution isn't permanent; if you remove the charged body, the conductor will return to its original condition.

To observe charging by induction, you will bring a charged insulating rod near a conducting sphere, like the one shown in Figure 9-10. To find how charge is distributed over its surface, you will touch it with a smaller conducting wand, called a “proof plane”. The proof plane, shown in Figure 9-11, will then be inserted into the Faraday ice pail, allowing you to find the polarity (+ or -) of the charge that is on the larger conducting sphere.



Figure 9-10. Conducting sphere, supported by an insulating base. When you move the sphere, touch the base, not the sphere, to avoid disturbing its charge.



Figure 9-11. A proof plane is used to extract a sample of charge from a larger body. It is a small conducting disk supported by an insulating rod. When you touch it to another conductor, some of the charge on the other conductor will flow to the proof plane. You can then insert the proof plane into the Faraday Ice Pail to measure the polarity of the charge.

You will use the electrometer, adjusted to its most sensitive scale (3 Volts).

A. One sphere

1. Locate the sphere > 1 meter from the Faraday Ice Pail
2. Use the electrometer and Faraday Ice Pail as in Part I (Don't forget to ground the sphere!).
3. Rub a polymer rod (e.g. PVC tube) with wool, and insert into Faraday Ice Pail to determine the polarity (+ or -) of its charge, and record this result.

4. Now hold the rod about 4-5 cm of the sphere. While holding the rod there (don't remove it during all these steps):

- a. Ground the electrometer
- b. Breathe on the proof plane to neutralize its charge
- c. Touch the metal pad of the proof plane to the far side of the sphere, as shown in Figure 9-12.
- d. Insert the proof plane into the Faraday Ice Pail to determine the polarity of its charge (+ or -) and record this result.
- e. Repeat for the near side of the sphere.

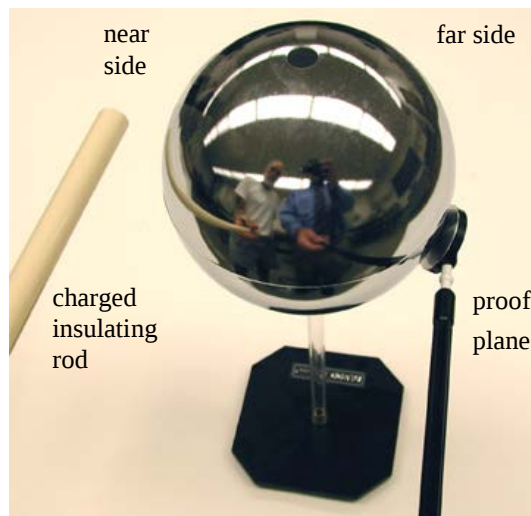


Figure 9-12. Using a charged insulating rod to induce a charge on a conducting sphere. The proof plane is used to collect a sample of the charge on the larger conducting sphere.

B. Two spheres

1. Position the two spheres > 1 m from the Faraday Ice Pail
2. Make the two spheres touch as in Figure 9-13.
3. As in Part A, rub the polymer rod with wool, and test the polarity (+ or -) its charge and record this result.
4. Bring the rod about 4-5 cm of one of the two spheres as in Figure 9-13 (a).

5. While holding the rod there, separate the two spheres by several centimeters by moving the far sphere away from the near sphere.



(a) Induce a charge, while both spheres touch.

6. Now set the rod down, far away from the spheres and the electrometer. Ground the electrometer. Breathe on the proof plane and use it to test the polarity (+ or -) of the far sphere as shown in Figure 9-13(c) and record this result. Repeat for the near sphere.



(b) Move the far sphere a few cm away. Separation should be larger than that shown in the figure.

7. Turn off the battery-powered electrometer.



(c) Sample the charge on one sphere, then the other.

Figure 9-13. Procedure for Part B, with two spheres. Be sure that the charged insulator is held in place while separating the two spheres in step 5.

Part III: Clean Up

- Unplug cables.
- Turn off instruments.
- Tidy the lab bench.
- Exit any running software.

Sample Calculations Summary

Part I: Triboelectric charging

1. Charge of objects, page A9-10.

Analysis Questions

Part I: Triboelectric charging

1. Consider the case of the charge producer wands:
 - a. Are the wands that have been rubbed together *always* charged equally and opposite when you measure them?
 - b. Explain how you drew this conclusion. If your answer to (a) is *No*, can you suggest any mechanisms to account for this discrepancy?

EXPERIMENT A11:

Ohm's Law



$$V = IR$$



$$R_{\text{series}} = R_1 + R_2$$

Objectives:

- *Scientific:* Verify Ohm's Law.
- *Scientific:* Learn about series and parallel circuits.
- *Skill development:* Learn about resistors.
- *Skill development:* Learn to use power supplies and multimeters.

Introductory Material

Ohm's Law is not a fundamental law of nature. It's phenomenological. Some materials obey it, some don't. As it happens, most materials do obey it. A copper wire, a lump of mud, and even your sweaty skin ... these materials happen to obey Ohm's Law.

Ohm's Law deals with two things:

- the current I that passes through an object,
- the electric potential drop ΔV that is applied across the object.

For most materials, the two are proportional, $I \propto \Delta V$.

When you look at the relation $I \propto \Delta V$, you can see that there must be a proportionality constant. That constant is the resistance of the material, R , which has units called ohms (Ω).

Ohm's Law can be written two equivalent ways:

$$I = \Delta V / R \quad (11.1)$$

$$\Delta V = I R \quad (11.2)$$

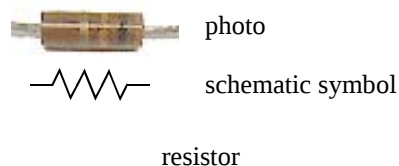
There are some things we should say about an object's resistance, R :

- R depends on the material. Specifically, it depends on the resistivity (ρ) of the material. Resistivity is measured in $\Omega \cdot \text{m}$.
- R also depends on the geometry of the object.
- If the material has a uniform cross section, (such as a wire or the rectangular compartment of water you will investigate in Part V), the resistance is given by:

$$R = \rho \frac{l}{A} \quad (11.3)$$

where l is the length of the material and A is the cross-sectional area.

- R can also change significantly with temperature, which is one reason that some materials do not follow Ohm's Law.



There's another important thing about resistances. Since you can connect two objects together, you can also connect their resistances together. And in general, there are two ways of doing this:

- Series means one after the other.
- Parallel means one beside the other.

When you connect two resistors in series, it turns out that they look like a single resistor R_{tot}

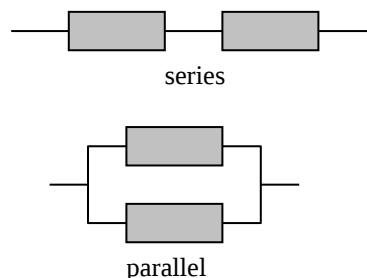


Figure 11.0 Series and parallel circuits.

$$R_{\text{tot}} = R_1 + R_2 \quad (11.4)$$

And when you connect them in parallel,

$$R_{\text{tot}}^{-1} = R_1^{-1} + R_2^{-1} \quad (11.5)$$

Note that resistances in series add, whereas resistances in parallel add through their reciprocals.

Pre-Laboratory Questions

- 1 Suppose that you are given a resistor with the following colored bands:
Grey, orange, red, silver.
What is the resistance R , and the % tolerance of this resistor? (See Figure 11-6.)
- 2 What current I will flow through a $500\ \Omega$ resistor, if a 9-Volt battery is connected across it?

Equipment List

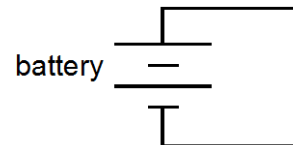
- * multimeter
- Power supply (0-15 V DC) (Agilent E3610A or similar)
- 1.5 Volt batteries (2)
- 6 V lightbulbs (2)
- Decade box
- Board with resistors
- * Computer

* indicates that an item is described in the Instrument Glossary.

Be careful not to short-circuit the battery.

A short circuit is when a wire makes a closed path from one battery electrode to another. If you do create a short circuit, the battery will get hot and it will soon lose its charge and become worthless.

If you should discover that the battery is hot, immediately disconnect it.



DON'T DO THIS:
this battery has been short-circuited.

Experimental Procedure

Part I: Gaining Familiarity with Multimeters

A. DC Voltage

1. Examine your multimeter and the photos shown in Figure 11-1. Be sure that you know which connectors at the bottom to use for three kinds of measurements.
2. Install the test leads (i.e., wires) in the correct holes to measure voltage, as shown in panel (a) of Figure 11-1. Check that you do NOT install the test leads in the holes for measuring current, panel (c) of Figure 11-1, or you will blow a fuse.
3. Turn the multimeter off and then adjust the multimeter selector switch to DC voltage



(a) Voltage V

(b) Resistance Ω

(c) Current A

Figure 11-1: Multimeters. The meter can measure voltage, resistance and current. Note two things:

- which connectors at the bottom are used
- where the dial points (your dial might look different from the one shown here, but somewhere it will have V , Ω , and A for measuring voltage, resistance, and current).

4. Always use these conventions: black is common (COM or GND), red is positive (+).
5. Use the board with two batteries, shown in Figure 11-2. Turn on the multimeter. Measure the voltage of each battery separately. Depending on how fresh your batteries are, their voltages may differ from the nominal voltage of a carbon-zinc cell (1.56V).
6. Using the voltages of the two batteries that you measured in the previous step, calculate the total voltage that you expect if you were to connect them in series, as shown in Figure 11-3. Show your work in a SAMPLE CALCULATION.
7. Connect the batteries *in series* and measure the total voltage. (See Figure 11-3).



Figure 11-2. Board with two batteries.

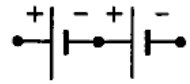


Figure 11-3. Two batteries connected in series.

B. DC Current and a Test of Ohm's Law

8. Hook up the circuit shown in Figure 11-4 using *one* battery and a $50\ \Omega$ resistance. (You may use a decade resistor box for this purpose.) Measure the dc voltage ΔV .
9. Disconnect the circuit and then hook it up according to Figure 11-5. (Do not accidentally set the decade box lower than $50\ \Omega$ for this circuit.)
10. Connect the multimeter using the correct connectors for measuring *current*, as shown in Figure 11-1 (c) .
11. Note that the switch on the multimeter allows you to select either DC  or AC  current. Here you want to select DC.
12. Measure the current I through the resistor. Be sure to record the value as Amps, not

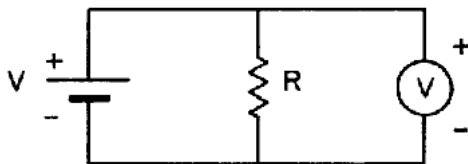


Figure 11-4. Using a multimeter (shown by the circle with a V) to measure voltage, as shown in Figure 11-1(a)

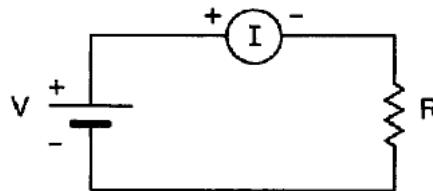


Figure 11-5. Using a multimeter (shown by the circle with an I) to measure current, as shown in Figure 11-1(c) .

milliamps.

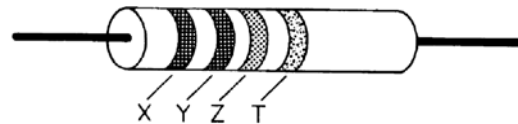
13. Calculate the resistance value using the voltage ΔV and current I from the above two measurements, using Ohm's law.
14. Disconnect your circuit and reconfigure it with two batteries *in series* to obtain approximately 3 Volts and repeat the voltage and current measurements. Calculate the resistance. Show your work in a SAMPLE CALCULATION.
15. Disconnect the wires and turn the multimeter off.

Part II: Resistors

A. Resistor Values

The nominal resistance of a resistor is indicated by four colored bands on the resistor. The values are listed in the table in Figure 11-6. Here's how you read them:

- The *value* of the resistance is determined by writing the numerical value of X followed by the numerical value of Y, which is then followed by the number of zeros corresponding to the numerical value of Z.
- The *tolerance*, or range of possible values, of the resistance is given by the color of the fourth band as shown in Figure 11-6.
- Example: a resistor with green, blue, red, silver would be $56 \times 10^2 = 5600 \Omega$, with a tolerance of $\pm 10\%$.



Color	XYZ	Color	T
Black	0	Blank	20%
Brown	1	Silver	10%
Red	2	Gold	5%
Orange	3		
Yellow	4		
Green	5		
Blue	6		
Violet	7		
Gray	8		
White	9		

16. Turn off the multimeter. Check that the test leads are inserted in the correct holes for measuring resistance, as shown in Figure 11-1(b). Turn on the multimeter.
17. Examine the board with five mounted resistors and enter the color codes for each resistor onto your worksheet.
18. Measure the value of the color-coded resistors. Is the measured value the same as the color code value as decoded according to Figure 11-6, within the rated tolerance of the resistor?

Figure 11-6. Resistance color code.

Interesting notes about your body's resistance:

- (a) Lie detector tests often use a measurement of skin resistance to see how sweaty you are.
- (b) What is a dangerous voltage? A better question is what is a dangerous current. If a current passes from one arm to another (through your heart), you could be electrocuted with as little as 0.1 amperes. (A multimeter is powered by a small battery, which cannot produce such a large current.)

19. Measure your body resistance between your two hands, first with fingers dry, then wet. Use a high resistance scale on the multimeter.

B: Series and Parallel Resistors

20. Measure the resistance of each of two mounted resistors with a nominal value of $100\ \Omega$, as shown in Figure 11-7.
21. Calculate the total resistance that you expect the two resistors to have, when they are connected in *series*. In doing this calculation, use the measured values (not the nominal values). Show your work in a SAMPLE CALCULATION.
22. Calculate the total resistance that you expect the two resistors to have, when they are connected in *parallel*. In doing this calculation, use the measured values (not the nominal values). Show your work in a SAMPLE CALCULATION.
23. Now measure the total resistance when they are combined in series. Compare to the value calculated above.
24. Now measure the total resistance when they are combined in parallel. Compare to the value calculated above.
25. Adjust the power supply to 5 Volts. Connect the two lights so that they are in parallel, and connect them to the power supply (not the batteries!) See Figure 11-8. Increase the current limit (the knob marked "current" on the front panel of the supply; it sets the maximum current the supply can output) until the green light marked CC is extinguished and the light marked CV is on. Disconnect a wire from one of the bulbs. What happens?
26. Repeat the previous step, this time connecting the lights in series. In which case, parallel or series, did the lights appear brighter, and in which case did the lights appear dimmer? Disconnect a wire from one of the bulbs. What happens?

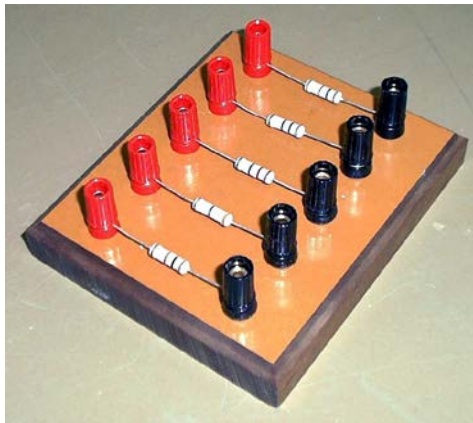


Figure 11-7. Board with resistors.

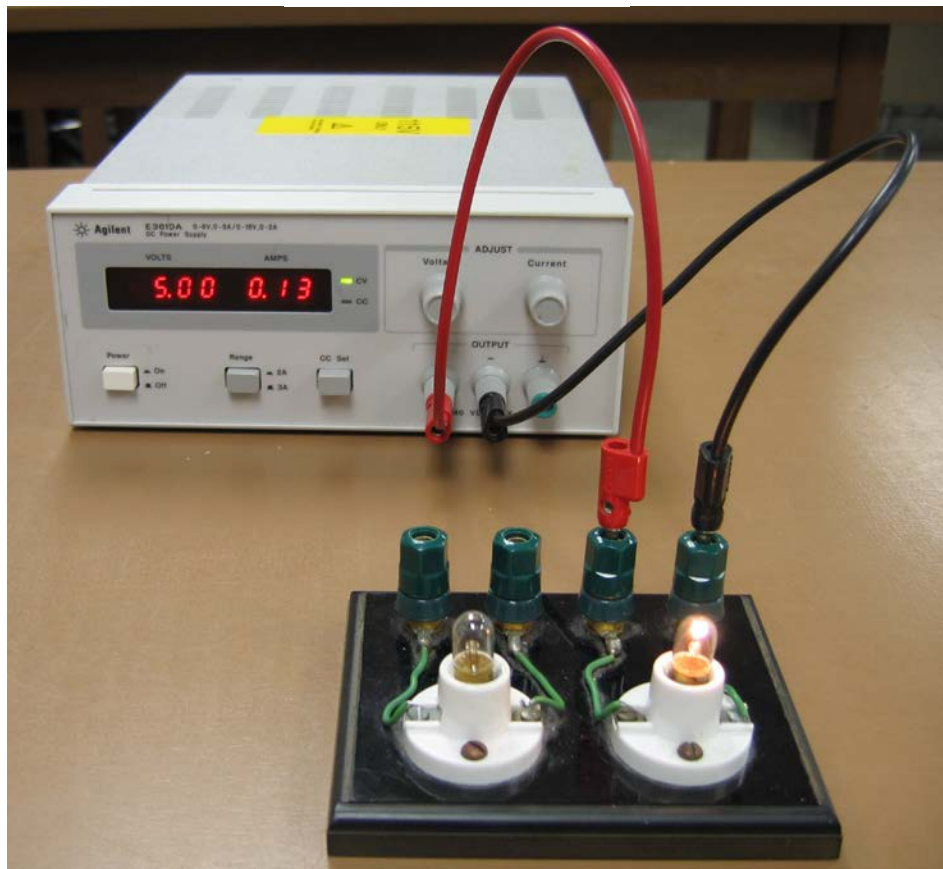


Figure 11-8. One light bulb connected to the power supply. You will have to determine for yourself how to connect two bulbs in parallel or in series.

Part III: Measure ΔV vs. I

Here you will make a plot of voltage vs. current for a resistor, and use it to find its resistance.

- Turn the multimeter and power supply off. Hook up the circuit shown in Figure 11-9, using the power supply, multimeter and decade box.
- You will use the multimeter to measure *current*. Insert the test leads (i.e., wires) into the multimeter inputs “COM” and “A”.
- The steps described in the previous two bullets **must** be completed before completing the following steps.
- Before turning the power supply or multimeter on:
 - ❑ Turn the “Voltage Adjust” knob fully counterclockwise, as shown in Figure 11-11.
 - ❑ Turn the “Current Adjust” knob fully counterclockwise and then $\frac{1}{4}$ turn clockwise, as shown in Figure 11-11.
 - ❑ The “Range” button may be in either the *in* or *out* position. It doesn't matter.
 - ❑ Adjust the resistor decade box to $200\ \Omega$, as shown in Figure 11-12. (Do not accidentally use a resistance less than $200\ \Omega$.)
 - ❑ Connect banana plug cable leads to the common (COM) and current (A) connectors on the multimeter, as shown in Figure 11-13, so that the current passes through the multimeter.

Figure 11-9: Setup for Part III.
See also Figures 11-10, 11-11, 11-12, and 11-13

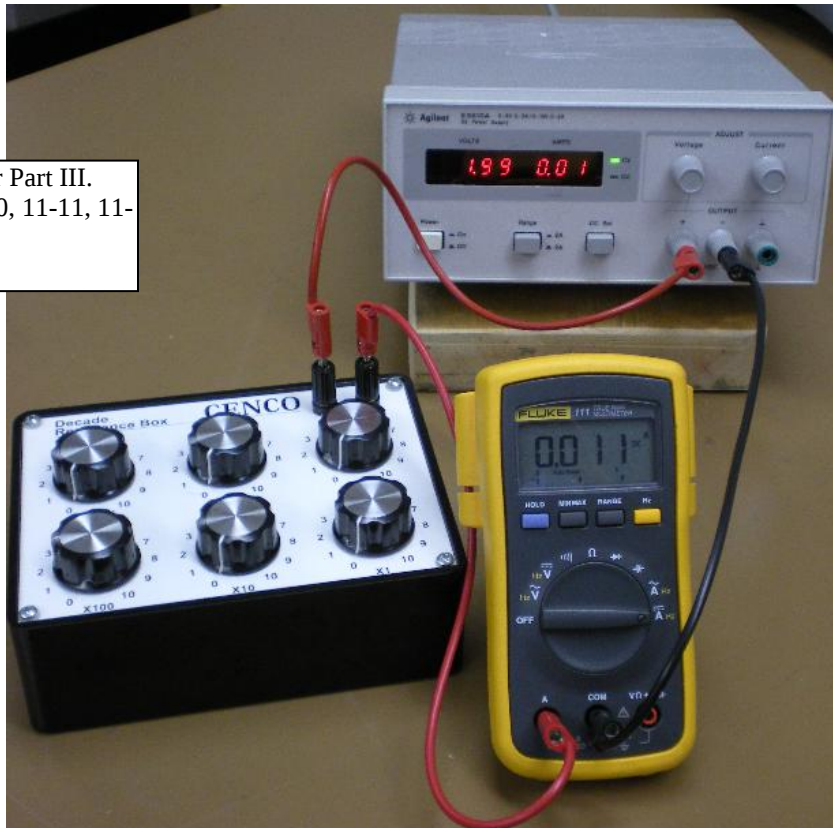
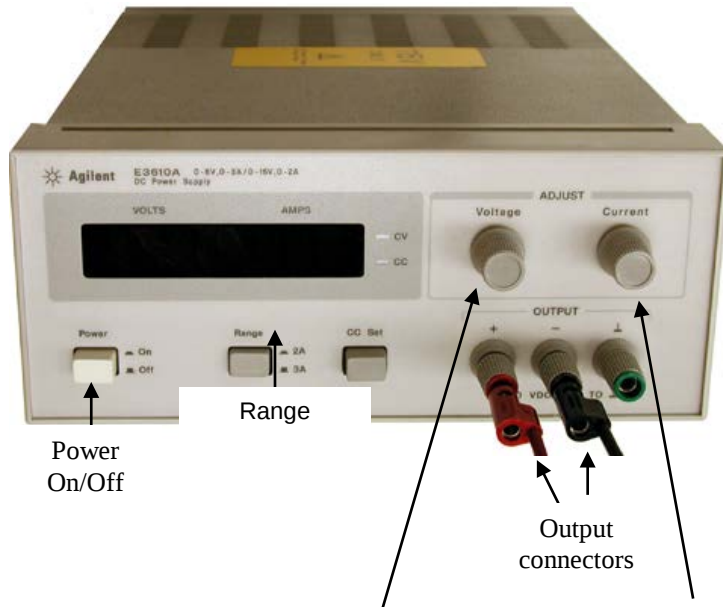


Figure 11-11. Agilent E3610A Power supply.



Figure 11-10. Adjust the multimeter for a 20 mA scale. Be sure to select DC, not AC current. (Your meter may look different.)



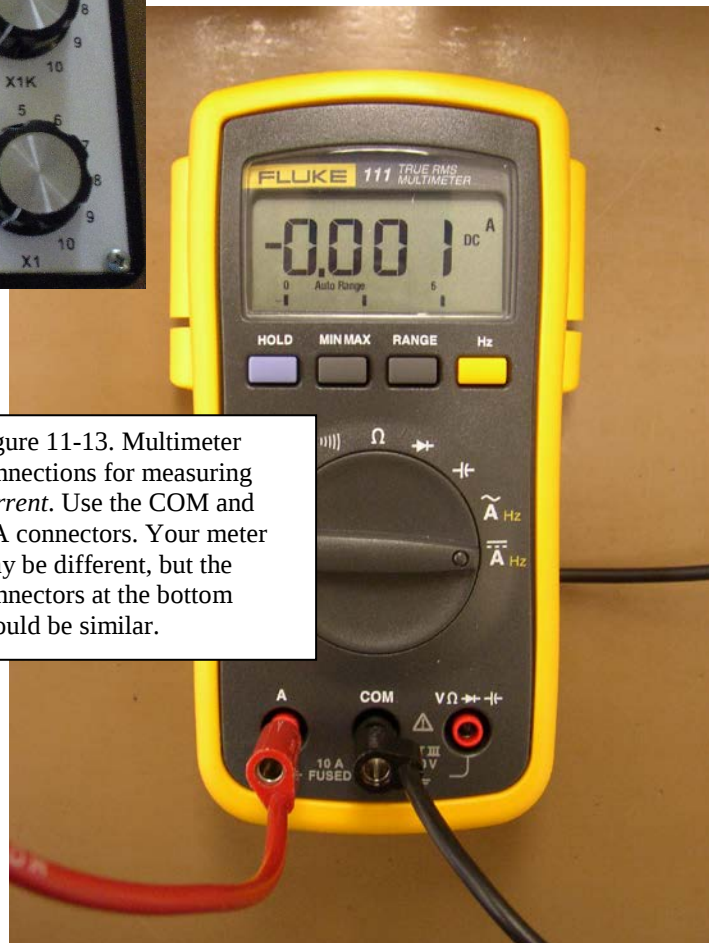
Voltage Adjust:
initially this should
be turned fully
counterclockwise.

Current Adjust:
initially this should
be turned fully
counterclockwise and
then ¼ turn
clockwise.



Figure 11-12. Adjust the decade box for 200 Ω as shown here.

Figure 11-13. Multimeter connections for measuring current. Use the COM and mA connectors. Your meter may be different, but the connectors at the bottom should be similar.



- Turn on the power supply and multimeter. Check that the power supply's "CV" light is on (to indicate that the power supply is running in a Constant Voltage mode, as compared to a Constant Current mode).
- You will read voltage ΔV from the power supply digital display, and current from the multimeter.
- Adjust the output voltage to 3.0 V, and record the current. Be sure to record the current in Amperes, not in milliAmps.
- Repeat for 4.0 V, 5.0 V, ...10.0 V.

IMPORTANT: At some point you may notice that even though you are turning the voltage knob, the voltage is not increasing. If so, then immediately STOP trying to increase the voltage. Turn the voltage knob back down until the voltage actually starts dropping. Turn the current knob up slightly so that the CV light comes back on. Resume your experiment, and repeat this step as necessary.

- Using computer software such as Logger Pro, plot the voltage ΔV on the vertical axis and the current I on the horizontal axis.
- Do a linear fit on your data.
- Record your slope in units of resistance.
- Attach your plot to your worksheet.

Part IV: Clean Up

- Unplug cables.
- Turn down the voltage on the power supply and turn it off.
- Be sure to turn off the battery-powered multimeter.
- Tidy the lab bench.
- Exit any running software.

Sample Calculations Summary

Part I: Gaining familiarity with multimeters

Page A11-6: Calculation of voltage of two batteries in series.

Page A11-7: Calculate the resistance.

Part II: Resistors

Page A11-8: Calculation of series resistance.

Page A11-8: Calculation of parallel resistance.

Analysis Questions

Part I: Gaining familiarity with multimeters

1. How do the dc voltage measurements for the two batteries separately compare to their measurements when they are connected in series?

Part II: Resistors

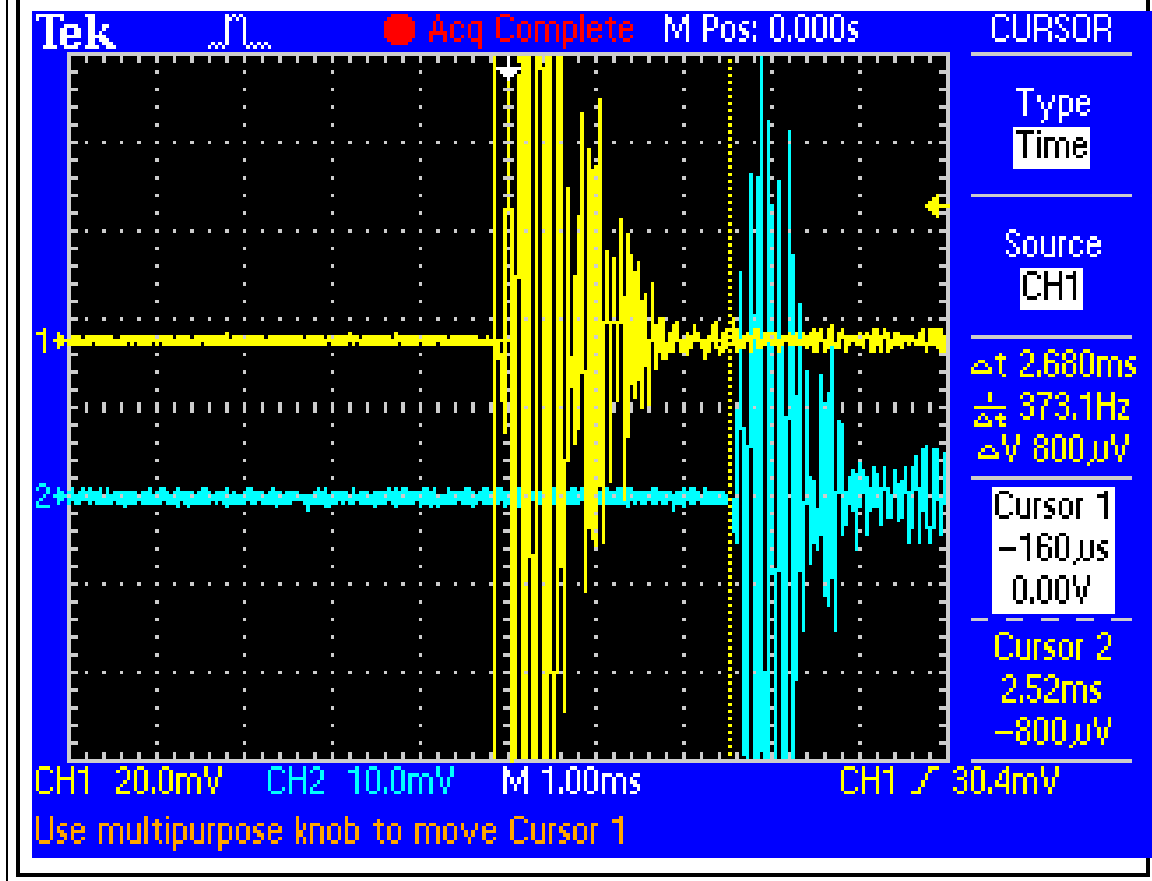
2. From your measured body resistance, calculate the voltage that could cause death by electrocution for (a) dry skin and (b) wet skin.
3. Resistors (in this case light bulbs) behave differently when connected in series or in parallel.
 - a. For procedure B25-B26, explain what happens in each case when one of the lights is disconnected.
 - b. If you have a string of standard, cheap Christmas lights and one bulb burns out, the whole string doesn't work. Are these lights connected in series or in parallel? Explain.

Part III: Measure ΔV vs I .

4. Calculate the % error between your slope and the resistance setting on the decade box. Why should the slope and the resistance setting be the same?

EXPERIMENT A12:

The Speed Of Sound



Objectives:

- Use the time-of-flight method to measure the speed of sound waves in air and compressional waves in solid materials.
- Learn to use a digital storage oscilloscope.

Introductory Material

In many aspects of your day to day life, it probably seems as if the speed of sound is infinite. If you are having a conversation with someone standing near you, it seems as if you hear their words as they are saying them. There is no perceptible delay. However, if you think a little more, you almost certainly do know from your experiences that sound doesn't reach your ears instantaneously. If you see a bolt of lightning in the distance, you probably aren't surprised when it takes a few seconds before you hear the corresponding thunder. This of course is evidence that sound travels much slower than light. While sound waves do travel rather fast compared to many things that you deal with on a daily basis, the speed of sound can be measured in a lab, and that is what you will be doing today.

In this experiment, you will use a time-of-flight method to measure the speed of sound. To do this, you will:

- cause a pulse of sound waves to travel past two microphones, separated by a distance Δx .
- measure the time interval Δt between the arrival of the pulse at the two microphones
- compute the speed of sound as the ratio $\Delta x / \Delta t$.

To measure Δt , you will use a digital storage oscilloscope, which is an instrument that makes a plot of voltage vs. time. The voltage you will measure is the signal from a microphone. The oscilloscope has two input channels, and you will use one for each of the microphones. The display will look something like Figure 12-1, where time is the horizontal axis, and the voltage output from the microphone is the vertical axis.

You will perform this measurement for sound waves in air and Compressional (P) waves in solid rods.

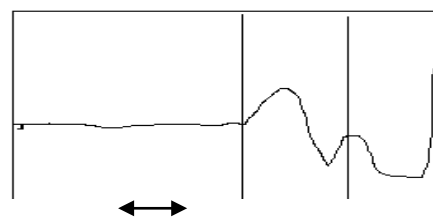


Figure 12-1. Sketch of display of digital storage oscilloscope. The vertical axis is the voltage output from a microphone, and the horizontal axis is time.

The speed of sound in air depends on the ambient temperature T according to:

$$v_A^{Th} = 20.1\sqrt{T} \quad (12-1)$$

where T is in Kelvin and v_A^{Th} is in m/s .

It turns out that in a *solid*, there is not just one, but two kinds of sound waves:

- The first is a longitudinal, i.e., *compressional* wave. This is sometimes called the “P Wave”. It is the same as a sound wave in air. The atoms or molecules move back and forth along the same axis as the direction the sound travels. This is like a sound wave in air.
- The second is a transverse, i.e., *shear* wave. This is sometimes called the “S Wave”. The atoms move sideways, compared to the direction the sound travels.

These two kinds of sound waves are important phenomena in seismology. In an earthquake, both kinds of waves are excited at the earthquake’s epicenter. At a distant point from the earthquake’s epicenter, you will first detect the compressional wave, and then at a later time you will detect the shear wave, because it is slower than the compressional wave.

Only a solid can sustain a shear sound wave. In a liquid or gas, the molecules or atoms can simply slide past one another, so that there’s no restoring motion for a shear displacement. In a solid, whether it is a piece of metal or the Earth’s crust, there is a restoring motion as atoms try to stay adjacent to the same neighbors. That’s why the shear wave can propagate in a solid. The way that geologists know that the Earth’s center is molten is that they can tell from earthquake data that only the compressional wave, not the shear wave, propagates through the Earth’s center. In this experiment, you will only measure the speed of compressional waves, as the shear waves are difficult to observe.

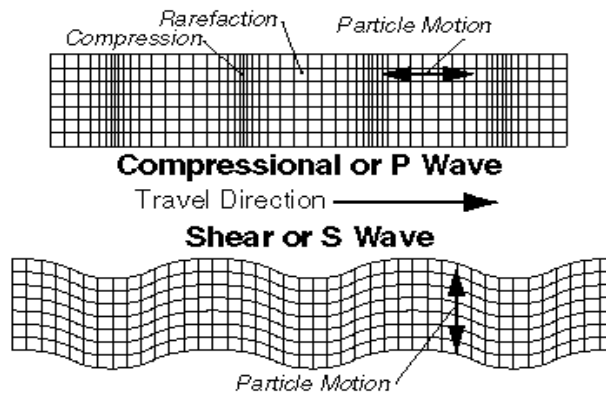


Figure 12-2. Compressional and shear waves in a solid.

The speed of the compressional (P) wave in a solid depends on whether the sample of material is *bulk* (i.e., very big compared to the wavelength of sound) or a *thin rod*. A table of values appears below (source: CRC Handbook of Physics and Chemistry).

	Aluminum	Polycarbonate	Steel	Water
Compressional Wave (Bulk)	6420 m/s	2270 m/s	5960 m/s	1497 m/s
Compressional Wave (Thin Rod)	5000 m/s	1447 m/s	5200 m/s	---

Pre-Laboratory Questions

1. Calculate the speed of sound in air at 24.1°C.
2. The picture on the first page is an oscilloscope trace produced from using the procedure for measuring the speed of sound in air as explained in the Experimental Procedure for Part I. The microphones are 0.914 m apart. Calculate the speed of sound for this case. If you get stuck, reading the Experimental Procedure for Part I may be helpful.
3. The speed of longitudinal waves in a thin rod is $v = \sqrt{Y/\rho}$, where Y is the Young's Modulus in N/m², which is a material property that measures how difficult it is to stretch the material, and ρ is the material's mass density in kg/m³. Calculate this sound speed in a thin steel rod, using the data below. Does sound travels faster in steel or air?

Material ¹	Young's Modulus Y (N/m ²)	Mass Density (kg /m ³)
Aluminum	6.5×10^{10} – 7.5×10^{10}	2700
Steel	2.0×10^{11} – 2.5×10^{11}	7880
Polycarbonate	2.0×10^9 – 2.4×10^9	1220

Equipment List

Digital Oscilloscope

Parts I and II:

Metal rods

Tie-clip microphone (2)

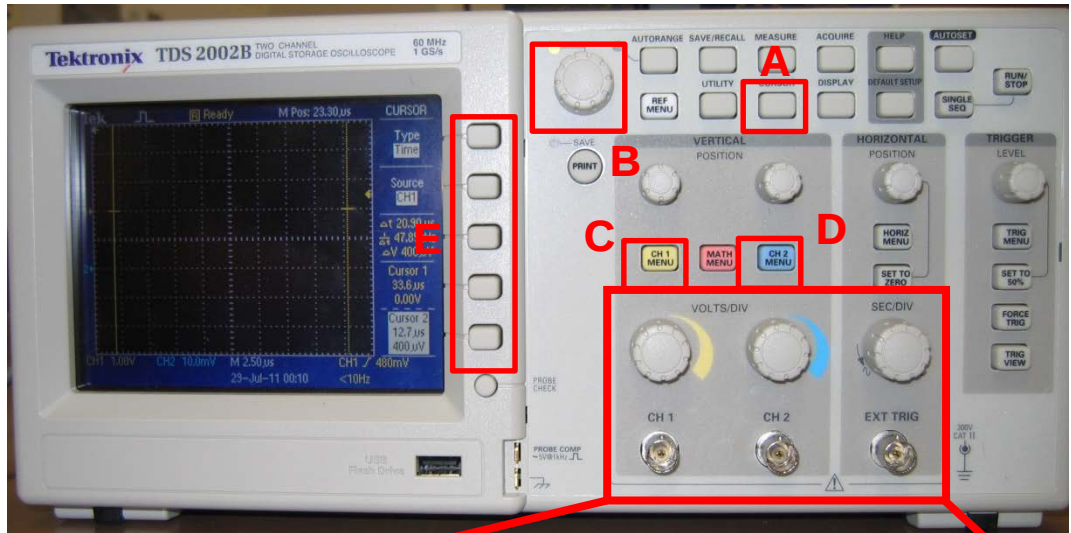
“Clicker”

¹ The metals listed here can be manufactured in various ways, and in various alloys.

Figure 12-3. Apparatus for speed of sound in air and rods.



Figure 12-4. Digital Storage Oscilloscope. The display will show the voltage on the vertical axis and time on the horizontal axis. Your two microphones will be connected to the two inputs, CH1 and CH2. You can adjust the vertical scale by turning the VOLTS/DIV knob, and you can adjust the horizontal scale by turning the SEC/DIV knob. Also note the location of the CURSOR button (A), the cursor knob (B), the Ch 1 and Ch 2 buttons (C, and D), and the menu buttons (E).



Note: The scope shown is a TDS2002B. If you are using a TDS2002C, the buttons are all in the same places, but some are labeled differently. For example, the SINGLE/SEQ button is now called “single”, the VOLTS/DIV knobs are labeled as “Scale”, and the SEC/DIV knob is also labeled as “Scale”.

Experimental Procedure

Part I: Speed of Sound in Air:

- Examine your oscilloscope. Identify the features listed in the caption of Fig. 12-4.
- The steel rod should already be in the rod holder assembly as shown in Figure 12-5a. If it is not, put the rod in the assembly.
 - Be careful not to over tighten the screws (this will be especially important later when you use the polycarbonate rod).
- Clip two microphones on the rod, separated by a distance $\Delta x \approx 1$ m. Make both microphones face the same direction as shown in Figure 12-5b.



Figure 12-5:

- (Left) Rod holder assembly.
 - (Right) Microphone alignment. Note that this picture is meant to show the microphone alignment only. In this picture the microphones are too close together and the rod is not in the rod holder assembly.
- As a matter of terminology, we'll say that the "first" microphone is the one that is facing away from the "second" microphone. Connect the first and second microphones to inputs CH1 and CH2, respectively.
 - At the bottom of the scope's display, check that the oscilloscope has the following settings:

CH1	20 mV/div
CH2	10 mV/div
SEC/DIV	1 msec
Trigger threshold	+30 mV
BW Limit:	ON

CH1 20.0mV/div CH2 10.0mV/div M 1.00ms CH1 / 30.4mV

- At the top of the scope's display:
 - Check that "Ready" appears at the top of the display. If not, press the RUN/STOP button. Then push the SINGLE SEQ ("single" on a TDS 2002C) button.
 - Check that the "M Pos" indicator shows "0.000 s." If not, adjust the "Horizontal Position" knob.



- Hold a clicker at a distance of about 20 cm from the first microphone. Hold it in a direct line with both microphones, not above them.
- Make a clicking sound.
- If you do not get a waveform that triggers properly (see Figure 12-7), try again by pressing the SINGLE SEQ (single) button to re-enable triggering and then make another clicking sound.
- Press the CURSOR button. A green light will turn on next to the cursor control knob at the top of the oscilloscope as shown in Figure 12-6.
 - Make sure that the cursor is set to measure time and not voltage.
- Select which cursor you want to adjust by pressing the button next to its name on the screen. The name of the selected cursor will be outlined in white as in Figure 12-6.
- Adjust the cursors as in Figure 12-7 so that the difference between them is the time delay Δt , for the sound reaching the two microphones.
- Read the value of Δt off the right side of the scope display as in Figure 12-7.
- Repeat for three trials.
- Quality check: If your results differ greatly from one trial to another, you are doing something wrong. Ask your TA for help.
- Average Δt for the three trials.
- Calculate $\Delta x / \Delta t$ using the average value of Δt .
- Measure the air temperature.
- Compare to the theoretical speed of sound in air by computing the percent error.

Not seeing the results you expect on the oscilloscope? Here's a list of things to check.

1. Is everything connected properly?
2. Check that the microphone is turned on.
3. If the microphone is turned on, check the batteries.
4. Are the oscilloscope settings correct?
5. Still can't figure it out? Ask your TA for help.

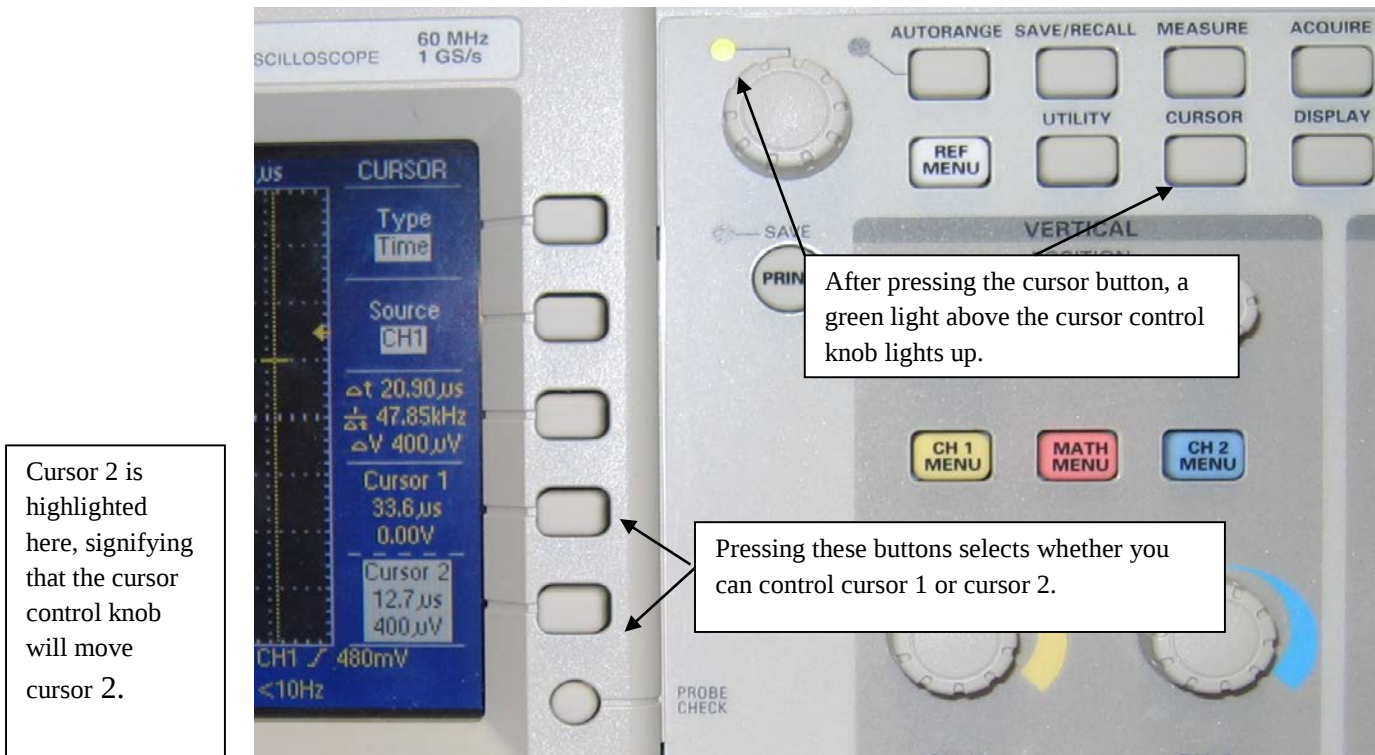


Figure 12-6. Selecting and adjusting the cursors.

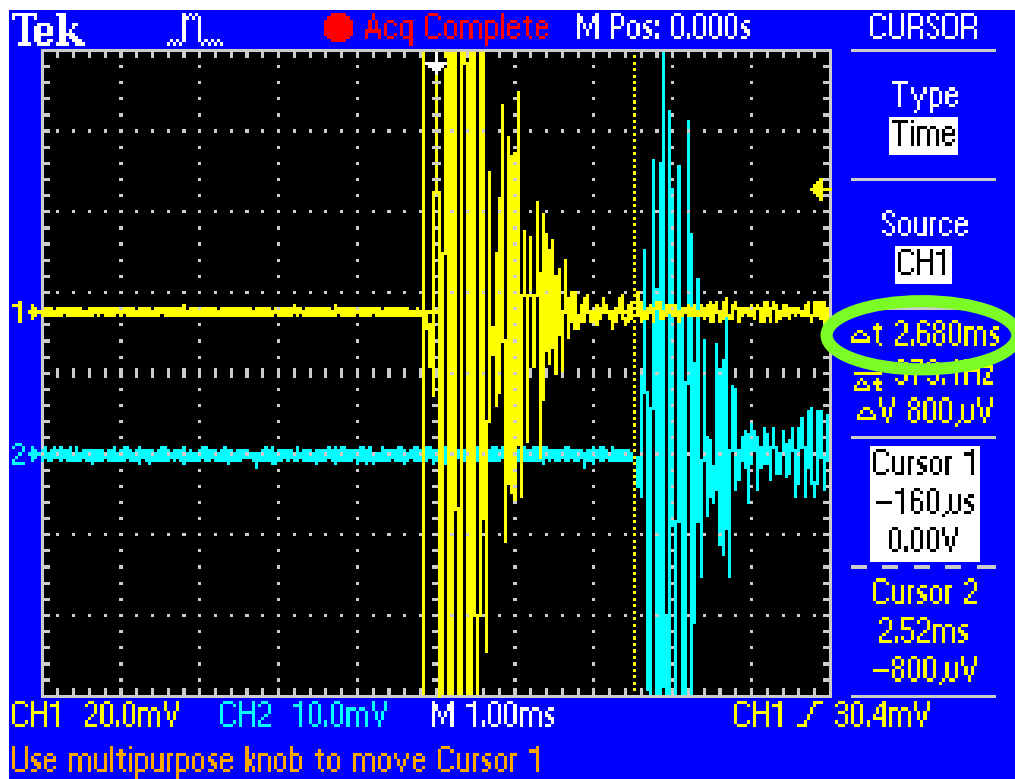


Figure 12-7. Oscilloscope display for time-of-flight measurement of sound in air. The lower waveform CH2 is for the second microphone, which is located farther from the source of the sound. The cursors are the vertical dotted lines. By positioning the two cursors to the beginning of the burst, you will measure the time difference Δt (see the green oval in the picture above).

Part II: Speed of Sound in Rods:

You will use the same setup as for the time-of-flight measurement in air. You will use three kinds of rods, and you will measure the compressional (P) sound wave speed.

- Since you just finished Part I, the steel rod should still be in the rod holder assembly with the microphones attached. If not, then put the steel rod back in the rod holder assembly and clip the two microphones back on the rod so that they are separated as far as possible. The minimum separation for this experiment to work properly is $\Delta x \approx 25$ cm.
- Measure the distance Δx between the microphones.

Adjust the oscilloscope so that it has the following settings, as shown in the photo:

CH1	10 mV/div
CH2	10 mV/div
SEC/DIV	100 μ sec
Trigger threshold	+2 mV
BW Limit:	ON

You can check these values at the bottom of the scope display, as shown in the photo:

CH1 10.0mV/div CH2 10.0mV/div M 100 μ s CH1 / 2.00mV

- At the top of the scope's display: Check that the "Ready" indicator appears at the top of the scope's display. If not, press the scope's SINGLE SEQ (single) button.
- Using a short metal rod as a striker, tap the end of the rod to excite a compressional (P) wave, as shown in Figure 12-8. You will try to achieve a waveform with good triggering, as shown in Figure 12-10.
- If you do not get a waveform that triggers properly (see Figures 12-9 and 12-10), try again by pressing the SINGLE SEQ (single) button to enable triggering and then tap the end of the rod again.

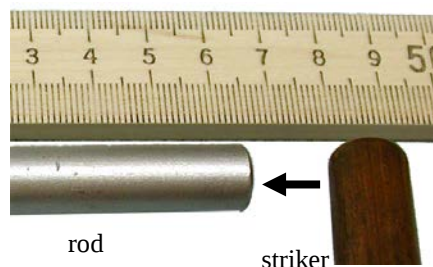


Figure 12-8.

Strike the rod on its end to excite the compressional (P) sound wave.

Figure 12-9. Example of bad triggering. This happens when the scope triggers on a peak in the waveform some time after the beginning of the sound. When this happens, try again.

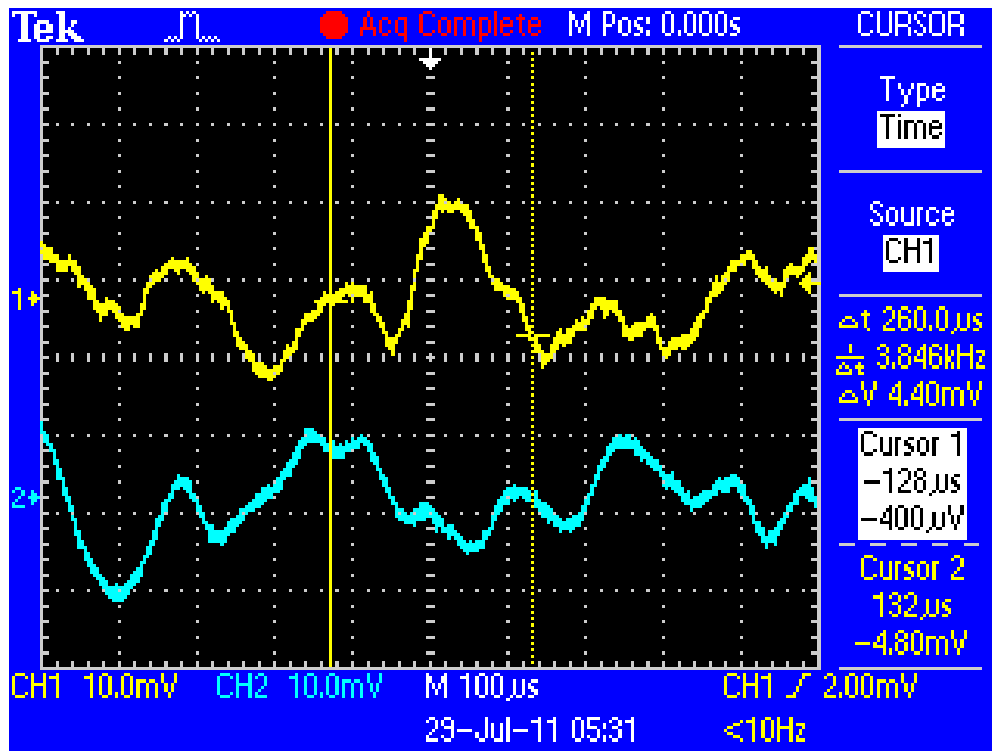
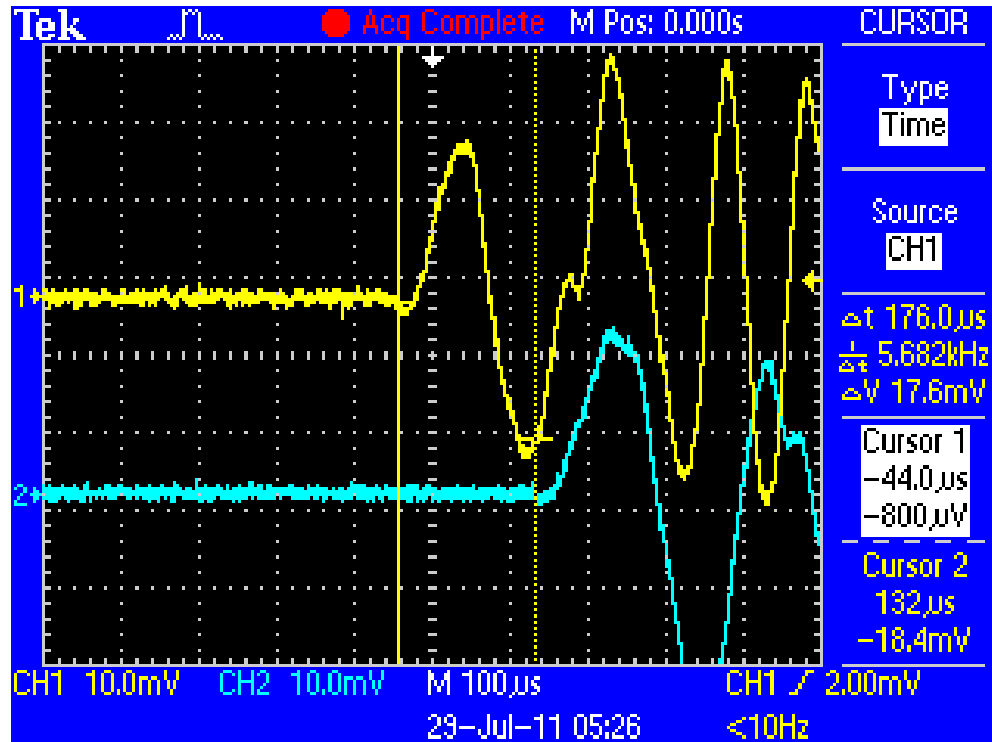


Figure 12-10. Example of good triggering. Use the cursors to measure Δt (Here, Δt is 176 μs). The cursors should be placed exactly where waveform begins to break. If you are inconsistent in making this judgment, your results will suffer.



- As you did with the speed of sound in air, measure the time-of-flight Δt of the leading edge of the pulse. Repeat for a total of three trials.
- Quality check: If your results differ greatly from one trial to another, you are doing something wrong. Ask your TA for help.
- Average Δt for the three trials.
- Calculate $\Delta x / \Delta t$, using the average value of Δt .
- Repeat your measurements with the aluminum and polycarbonate rods. Be especially careful not to over tighten the screws when putting the polycarbonate rod in the rod holder assembly.
- Compare your experimental result for the speed of compressional sound waves in the rods with the accepted value by calculating the percent error.

Part III: Clean Up

- **Turn off the microphones.**
- Tidy the lab bench.
- Turn off the oscilloscope.
- Exit any running software.
- Return the steel rod to the rod holder assembly.

Sample Calculations Summary

Show your work in Analysis Question #1 below.

Analysis Questions

1. The table to the right gives Young's Modulus for several metals. You are given a metal rod with a density of 19250 kg/m^3 . Using the methods of Part II, you determine that the speed of sound in this rod is 4587 m/s . Identify this metal.

Material	Young's Modulus $Y \text{ (N/m}^2\text{)}$
Aluminum	$6.5 \times 10^{10} - 7.5 \times 10^{10}$
Steel	$2.0 \times 10^{11} - 2.5 \times 10^{11}$
Osmium	5.5×10^{11}
Tungsten	$4.0 \times 10^{11} - 4.1 \times 10^{11}$
Copper	1.1×10^{11}

EXPERIMENT A16:

Geiger Counters and Radioactive Shielding



Objectives:

- Observe background radiation.
- Measure gamma radiation from Cesium 137 source.
- Observe dependence of radiation intensity with distance.
- Observe the effect of lead shielding on radiation intensity.

Introductory Material

The Geiger Counter

A Geiger tube counter is a radiation detector. It is simple, reliable and relatively rugged. Like all types of radiation detectors, the Geiger tube responds to charged particles. Therefore, it is more efficient (100%) for detecting α and β particles that can penetrate into the detector.

In this experiment, you will detect γ -rays, which have no charge. They are photons. To detect photons they must liberate some electrons that can be detected. This can happen either at the tube wall (by photoelectric emission) or in the gas that fills the tube (by ionizing the gas atoms). The probability for this conversion is about 8%.

The Geiger tube consists of a cylinder of gas with a wire running down the cylinder's axis. A large positive potential is applied to the wire. Here's how it works for detecting γ -rays:

- When a gamma-ray photon produces a free electron, either by recoil in the gas or photoelectric emission from a surface, that electron will initially have a considerable kinetic energy.
- It will then collide with gas atoms, and ionize those atoms. This will create a large number of free electrons, which have a low energy.
- Each of these electrons will collide with gas atoms, and if the electrons are accelerated sufficiently by the positive potential these collisions will occur at a sufficient energy to ionize even more gas.
- An avalanche of ionization ensues, so that an original energetic electron produces about 10^6 - 10^8 total electrons.
- Eventually the available energy is consumed, and the ionization ceases, and the event is over. The tube recovers in about 10^{-4} sec, when all the free electrons are either collected by the wire, or attached to gas atoms. The tube is then ready to "count" again.
- Electrons are collected by the positive wire, and their current can be detected electronically. The current has a pulsed waveform. This is the signal that is counted. Each pulse corresponds to a gamma ray that was detected.

The essential features of a complete counting system are shown in Figure 16-1. The four components inside the dotted outline are usually constructed inside a single "counter" unit and are shown as separated to emphasize their function.

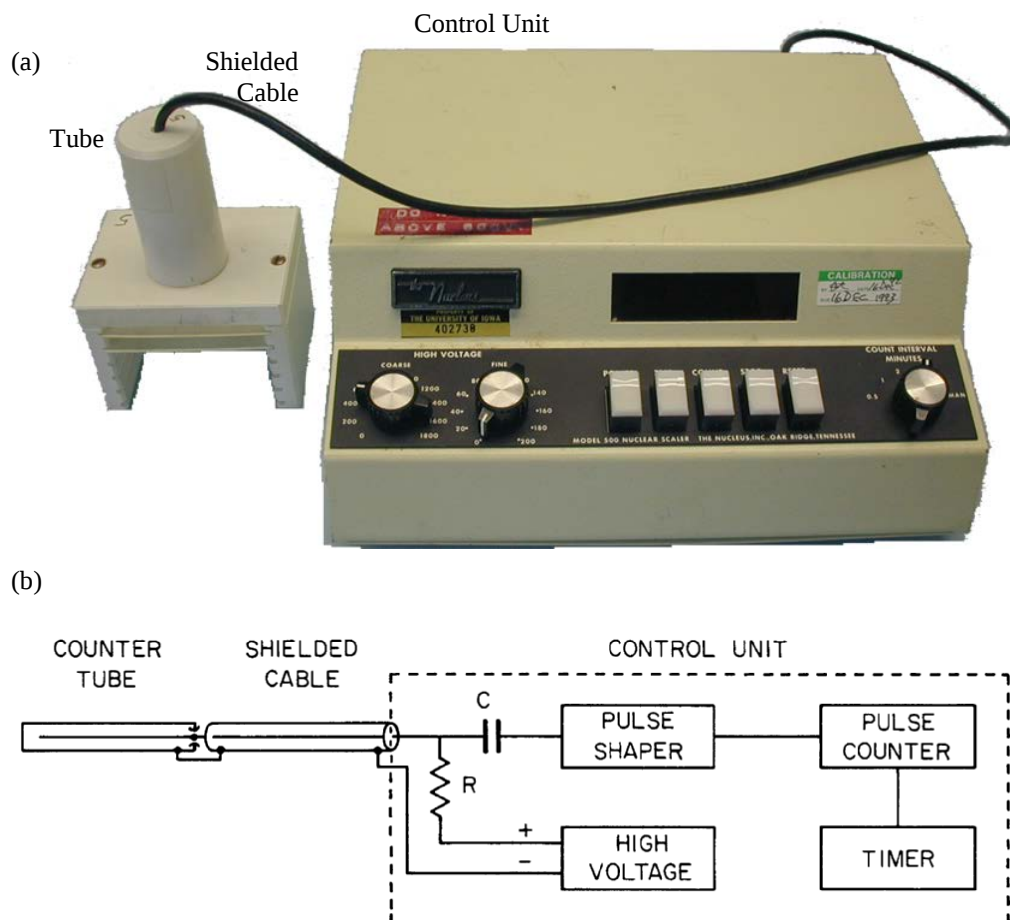


Figure 16-1. Geiger counter setup. (a) Photo. (b) Block diagram of components.

There are essentially two parts: the tube and the control unit. The high voltage power supply applies a positive bias to the center wire in the tube. The rest of the electronics in the control unit serves to detect and count the current pulses produced in the tube.

Radiation Safety

You might ask how much exposure to radiation you will receive while doing this lab.

Your dose X is measured in units called milliSieverts (mSv).

The background dose for people living in Iowa is typically 3 – 3.5 mSv / yr. Watching TV typically gives you a dose of 0.3 mSv / yr.

As a safety standard, The University of Iowa specifies a **dose limit of 1 mSv / yr** for the General Public (i.e., non radiation workers). That's for a whole-body exposure.

Your whole body dose for doing this experiment is approximately $X = 0.00064$ mSv. This dose is so low that you would have to do the lab about 1600 times per year to exceed the dose limit.

In this lab you will investigate two relatively simple methods for reducing dose: increasing the distance from the source, and placing shielding in front of the source.

Obtaining Information from a Graph

At this point in the course, you are probably quite familiar with plotting your data on a graph. In many cases this semester, you have probably noticed that your data was linear, meaning that you could fit it to a line of the form $y = mx + b$. You probably plotted your data in Logger Pro, used the linear fit capabilities of the software, and then used the slope of the graph to obtain the information you were looking for. If you did the projectile motion experiment, you found that some of your data was not linear, but rather parabolic (in other words, y depends not on x , but on x^2). Even though this is somewhat more complicated than the linear case, you were still able to fit the data and use the parameters of the fit equation to obtain information. In Part II of this experiment, you will plot and fit data as you have in previous experiments.

However, in Part III you will still plot your data, but you will not obtain a mathematical fit. In many real world cases, you will find that it may be a little more difficult to fit your data to a mathematical model. However, there is still valuable information that can be obtained rather quickly from a plot of the data.

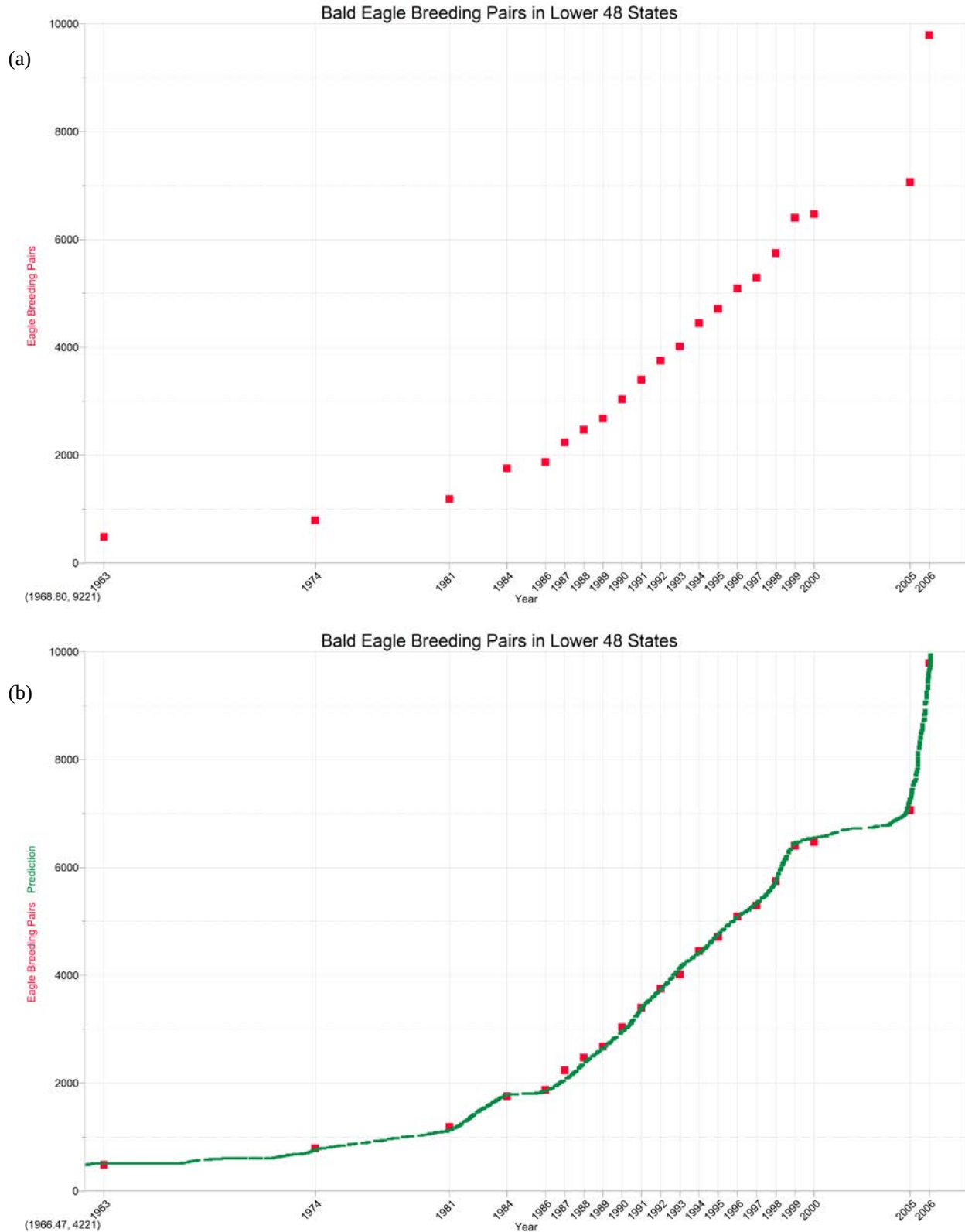
Here is an example:

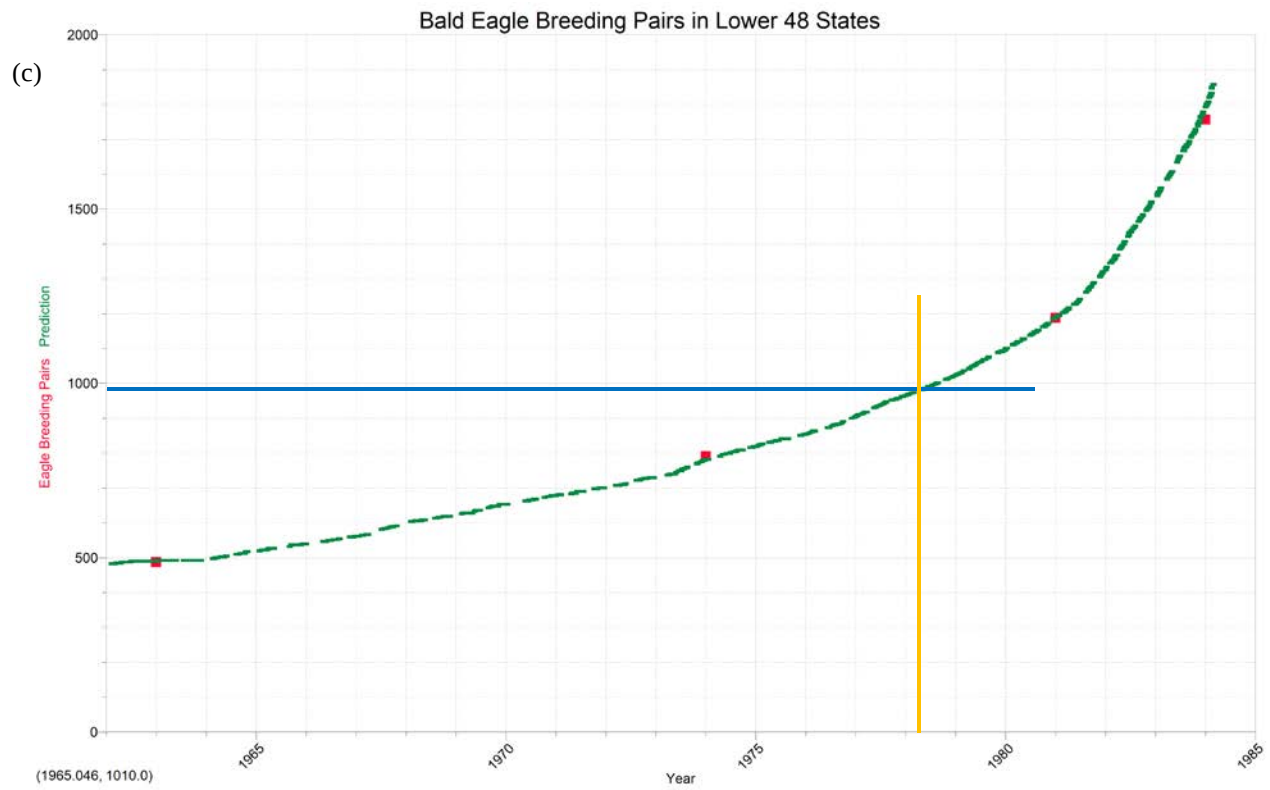
Figure 16-2(a) is a plot of bald eagle breeding pairs in the lower 48 states (Data from U.S. Fish & Wildlife Service, <https://www.fws.gov/midwest/eagle/population/chtotfprs.html>). Instead of fitting the data, we can obtain some useful information from this graph rather quickly. Let's try to figure out when the bald eagle population doubled from its initial value in 1963. From just looking at the graph, it appears that the initial population was just under 500 breeding pairs. In 1974 (the 2nd data point), the population hadn't doubled, but by 1981 (the 3rd data point), the population had more than doubled. Even though we don't have an exact data point for when the population doubled, we do know that the population doubled at some point between 1974 and 1981. But we can do better than that.

Now let's attempt to draw a curve connecting our data points as in Figure 16-2(b) (the green line). Figure 16-2(c) zooms in on the relevant portion of the plot. Now we draw a horizontal line (the blue line) at just a little below 1000 breeding pairs, which is about double the initial number of breeding pairs in 1963. We then draw a vertical (the orange line) where the

horizontal blue line crosses the line connecting the points. Following it down to the x axis, we see that the eagle population likely doubled by 1978.

Figure 16-2. Bald eagle breeding pairs. (a) Plot of data only. (b) A curve drawn in by hand to connect the data points. (c) Zoomed in to better see relevant part of plot.





Pre-Laboratory Questions

Go to the worksheet section at the back of this manual. You can write the answers to these Pre-laboratory questions on page A16-WS-3.

1. Table 16-1 shows a small portion of data used to create weight-for-age charts (Data from the CDC, http://www.cdc.gov/growthcharts/percentile_data_files.htm). Plot the data by hand (graph paper provided in worksheet section). Using the methods shown in the introductory material, determine at approximately what age (in months) that a child's weight will double from its weight at 120.5 months.

Table 16-1. Age and height information collected by the CDC for male children between the ages of 2 and 20 years.

Age (months)	Weight* (kg)
	*If we're being careful with our units, this should really be mass, not weight (weight is a force, with an SI unit of Newtons), but the CDC reports it as weight.
24.5	12.74
48.5	16.32
72.5	20.78
96.5	25.75
120.5	32.09
144.5	40.67
168.5	51.23
192.5	61.10
216.5	67.29
240	70.60

Equipment List

ID	Geiger Counter System
	Radioactive gamma-ray source (Cesium 137)
	Lead plates
	Lead absorption disks
	Calipers or micrometer
	Computer

“ID” indicates TA should collect an ID card as a deposit to issue this item.

Experimental Procedure

Part I: Background Radiation

Here you will see how there is a level of background radiation. This is useful for two purposes:

- ❖ To appreciate the issues involved in radiation safety, you must understand that you are always exposed to radiation, which comes from the Earth, buildings, etc., as well as cosmic rays. The background level depends on where you are. A brick building is more radioactive than a wooden one, for example.
- ❖ Later in the experiment, you will need to correct measurements made with a radioactive source by subtracting the background rate.

Follow this procedure to observe the background radiation:

- Put the source face up into the holder and set the voltage settings to 200 V on coarse and 0 fine. Turn up the fine voltage until counts start.
- Once you are sure you are getting counts, set the voltage 50 V above that level.
- Remove the source and make sure that all other radioactive sources are far away from your Geiger counter.
- Count for 10 minutes to determine the background counting rate, n_b in counts/sec. Record this value. You will use this value later to correct other measurements.



Figure 16-3. Set the High Voltage on the Control Unit to a value equal to 50-75 volts above the threshold value given to you by the TA. Do not exceed the maximum voltage indicated by the label on the top of the control unit.

This side should face up.

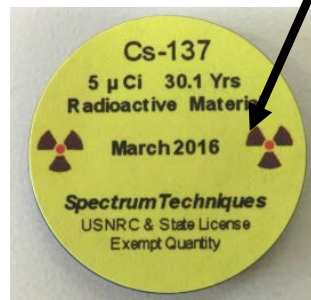


Figure 16-4. Cs-137 Source. This radioactive source has a half-life of 30 years, and it produces gamma rays. The source you are provided has a low level of 5 microCuries.

Part II: Intensity and Distance

Next you will test how changing the distance affects the intensity of radiation.

- Count with the source face up on each of the shelves. Use the following distances: $D = 1.6, 2.6, 3.6, 4.6, 5.6,$ and 6.6 cm. Count long enough to obtain good statistics.
- Compute the counting rate, in counts/sec
- Correct your data by subtracting the background count rate (using the value from Part I).
- Using software such as Logger Pro, plot counts/sec. ($n - n_b$) versus D .
- Fit your data by in two different ways:
 - Fit your data to a straight line using the  button.
 - Click on the curve fit button . Scroll down and select Nth Inverse (A/x^{n+B}). Select the power to be 2. Click “Try Fit”, then “OK”.
- Print your graph (make sure *both* fit equations are visible) and turn it in with your lab report.
- Which is the better fit, linear or $1/D^2$? One simple method of determining which is better is the eye test, but there is a numerical way. The Root Mean Square Error (RMSE) is a measure of how far away, on average, the data points are from the fitted curve. RMSE is in the units of the y-axis. The smaller the RMSE, the better the fit.



Figure 16-5. Detector Tube and Sample Holder.

The sample, and lead plates, can be inserted into the shelves of the sample holder.

Part III: Intensity and Lead Shielding

Use the following procedure to measure the intensity of radiation that passes through a sheet of lead, and to test its dependence on the thickness of the lead.

- Use four thicknesses of lead sheets from the kit, in the range 0.08 – 0.7 cm. Make sure you also collect data for a thickness of 0 cm (no shielding in place).
- The shield should be positioned on the second shelf from the top with the source directly beneath it to reduce scattering.
- Count at each thickness for the amount of time specified on the worksheet. You need to count longer for the thickest sheet in order to get enough statistics.
- Compute the number of counts per second.
- Subtract the background counting rate (from Part I) from all of your data.
- Make a plot of counts/sec.($n - n_b$) versus Thickness. You can either use the graph paper provided on the worksheet, or use Logger Pro. You will be extracting information from this graph the way you did in the pre-laboratory question, so you may find it easier to plot your data by hand.
- Draw a smooth curved line connecting your data points. If you choose to use Logger Pro, you can use the “Draw Prediction” option in the “Analyze” menu, or you can just draw your line in by hand after printing the graph. If you used Logger Pro, you must print your graph and turn it in with your lab report.
- From looking at your graph, it should be clear that adding lead significantly reduces the number of counts. Using the methods described in the introductory material, determine what thickness of lead you have to put in front of the source to cut the number of counts in half.



Figure 16-6. Lead absorption plate. You are provided several disks of various thickness.

Part IV: Clean-Up

- Turn off all instruments.
- Return radioactive sources to TA.
- Exit any running software.
- Tidy the lab bench.

Sample Calculations Summary

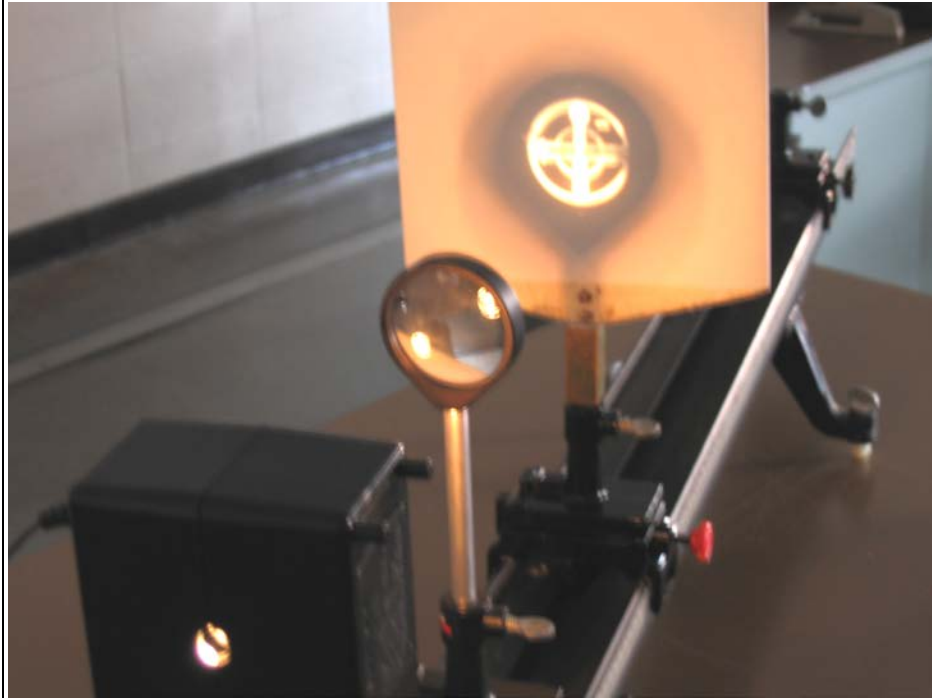
NONE

Analysis Questions

1. Does your data support a $1/D^2$ intensity dependence or a linear dependence? Explain.
2. Based on today's experiment, list two ways you could limit your exposure from a gamma-ray source.

EXPERIMENT A13:

Thin Lenses



Objectives:

- Measure the focal length of converging and diverging lenses.
- Test the thin lens formula.
- Study the magnification of a lens.

Introductory Material

In this experiment, you will measure the focal length f of two different lenses and test the thin-lens formula. We'll start off by reviewing some terminology.

First let's review the kinds of lenses. The biggest distinction is between **converging** and **diverging** lenses, which are compared in Figure 13.1. A converging lens is what you would find in a common magnifying glass.

Another term we use is **thin lens**. This refers to an idealized model for lenses, not an actual lens design. A thin lens has zero distortion.

The term **distortion** means that a straight line appears to be curved when it is viewed through a lens. You can verify from Figure 13.1 that the distortion is relatively small (although still noticeable, especially for the converging lens). Since the distortion is small, the thin lens equation will give a decent approximation for the behavior of these lenses.

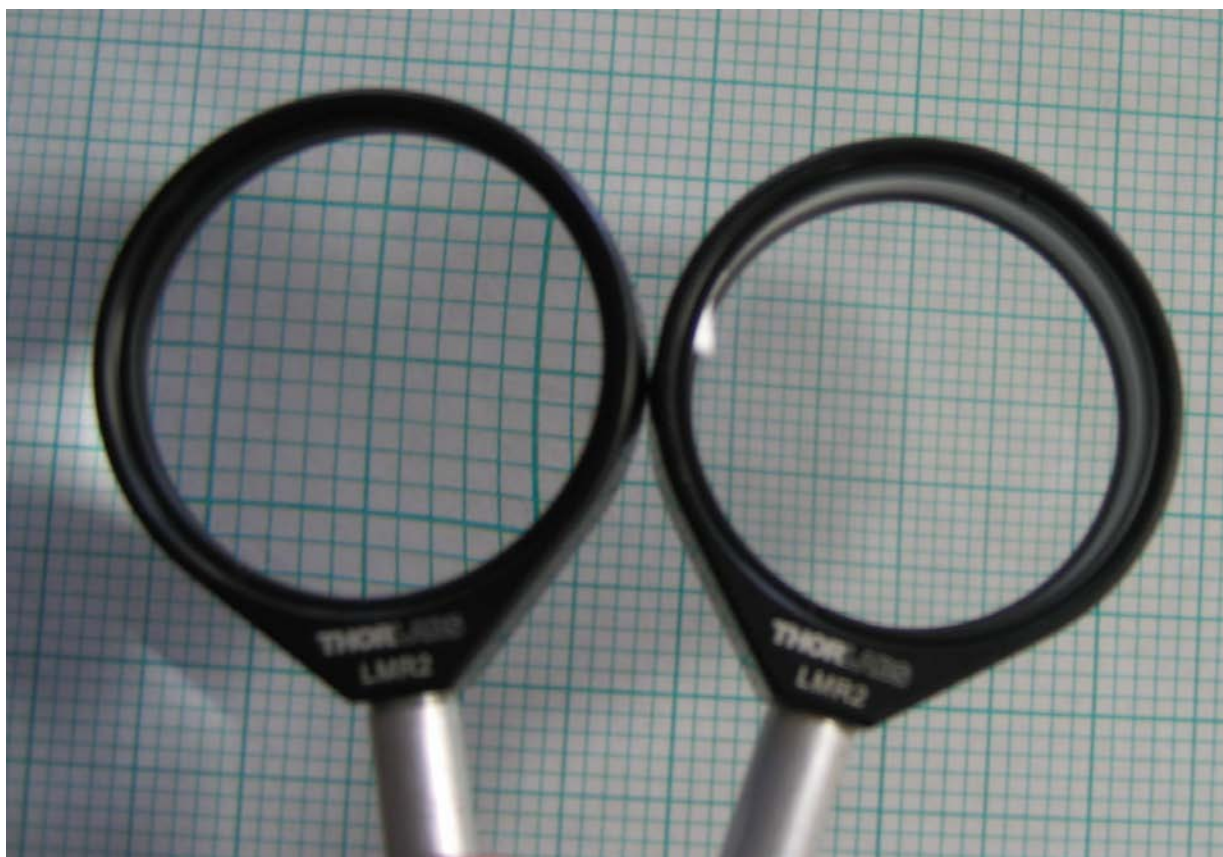


Figure 13.1 Two kinds of lenses:

“Converging”
“Convex”
“Positive”

“Diverging”
“Concave”
“Negative”

We often use **ray diagrams** to illustrate how a lens works. The simplest ray diagrams are for just a single lens, as shown in Figure 13.2

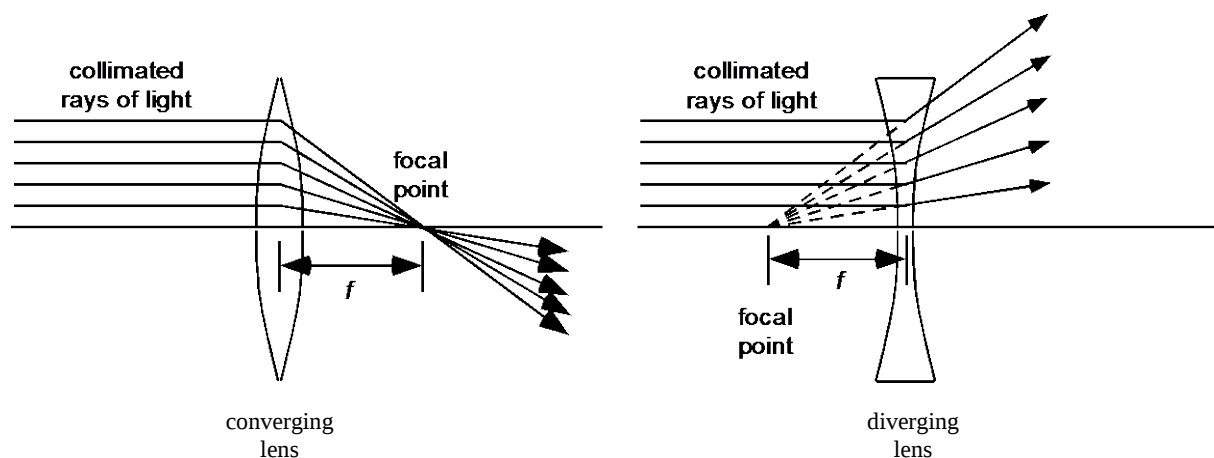


Figure 13.2 Ray diagrams for lenses.

In the examples shown, the incoming light is “collimated”, i.e., arriving in parallel rays. Note that the light passes through the focal point of a converging lens, but not for a diverging lens.

For the purpose of viewing something, a lens is something that turns an **object** into an **image**. These terms are illustrated in Figure 13.3 and 13.4. Images can be real or virtual, as compared in Figure 13.5

Images are distinguished by whether they are **real** or **virtual**. Light rays pass through a real image, but not through a virtual image. Only a real image can be seen on a screen. This is illustrated in Figure 13.5, which also explains how to make a ray-tracing diagram.



Figure 13.3. “Object” and “image.” Here, the sheet of graph paper is the “object”. What you see through the lens is the “image.”



Figure 13.4. An “object” you will use is this back-lit cross. The backlighting itself isn’t of interest; it merely helps provide good contrast so that you can easily see the cross. There’s an arrow on the cross so that you can tell whether an image of it is inverted.

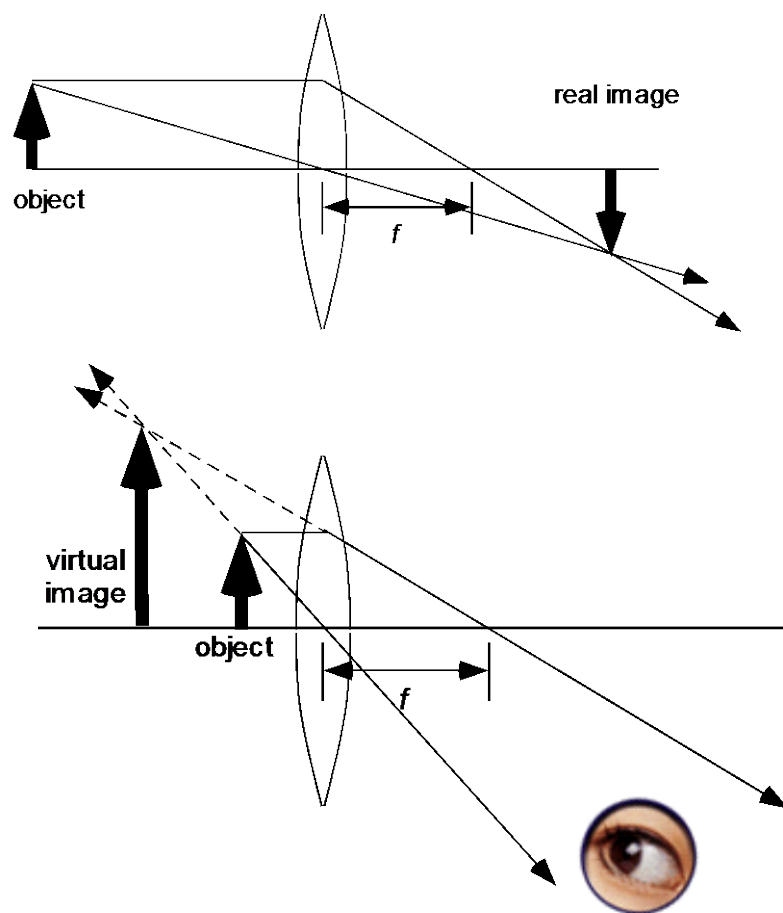


Figure 13.5. “Real” and “virtual” images.

An “image” is what you see when you look through a lens. The image is:

- *Real* if light actually passes through the point where you see the image.
- *Virtual* if it is located someplace where the light did not physically pass.

These sketches are examples of “ray tracing.” Here’s how to trace rays:

- We draw two rays coming from the tip of the object:
 - o One ray passes through the lens’s center. This ray isn’t bent.
 - o The other ray passes parallel to the optical axis until it gets to the lens, and there it is bent so that it passes through the focal point of the lens.
- The image is located where the two rays intersect.

We will test the thin lens formula, which is

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f} \quad (13.1)$$

where

i is the distance from the lens to the *image*, and
 o is the distance from the lens to the *object*

There are sign conventions that are used for the thin lens formula:

f is + for a *converging* lens
 f is - for a *diverging* lens

o is + if the object is real
 o is - if the object is virtual

i is + if the image is real
 i is - if the image is virtual

In Figure 13.6, we illustrate the distances o and i :

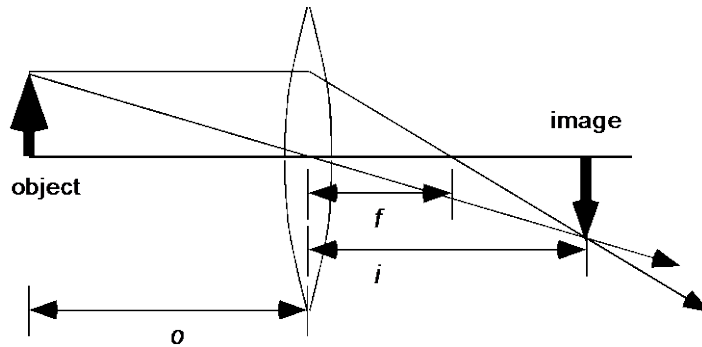


Figure 13.6. To use the thin lens formula, measure the distances o and i as shown here. All distances are measured from the lens's center. This lens is converging, and therefore f is positive.

Note that if you view a distant object, with $o = \infty$,

$$\frac{1}{\infty} + \frac{1}{i} = \frac{1}{f} \quad (13.2)$$

the image will be focused at the focal point, $i = f$. We will use this fact in our first measurement to measure the focal length of a lens by viewing an object that is far away.

We will also calculate the **magnification**. This is the ratio of the height of the image (h_i) to the height of the object (h_o).

$$m = \frac{h_i}{h_o} \quad (13.3)$$

Using the geometry of similar triangles, the magnification should also be equal to the following value:

$$m = -\frac{i}{o} \quad (13.4)$$

This is valid if the thin-lens model is correct. In the experiment, you will compare values for m from Eq. (13.3) and Eq. (13.4) to test whether the thin-lens model is accurate.

An image is **inverted** if it is upside down. The magnification is negative if an image is inverted.

Equipment List

Optics bench

Computer

Backlit (illuminating) object box

Graphical Analysis Software

Set of lenses

Graph paper

if a lens is dusty, clean it with alcohol and a special lens tissue, not with your clothes

telescope

Pre-Laboratory Questions

1. Use Figure 13.6 to perform the following steps, which are similar to what you will do in the lab:
 - a. Use a ruler to measure the distances i , and o .
 - b. Calculate the value of f that you expect, assuming the thin lens formula is correct.
 - c. Use a ruler to measure the distance f shown on the ray tracing diagram, and compare to the value computed from the thin lens formula, as a percent error.
2. Use a ruler to measure the required quantities in Figure 13.5 to compute the magnification. Report two magnification results: one for the real image, and one for the virtual image.

Experimental Procedure

Precautions:

- ❑ Don't drop the lenses or the telescope.
- ❑ Be careful when adjusting the telescope – there's nothing to stop you from pulling the eyepiece all the way out and then dropping it.

Part I: Converging Lens (Positive lens with $f = 10$ cm)

In this part, you will make several measurements of the focal length, f , for a converging lens and compare to the manufacturer's value of $f = 10$ cm.

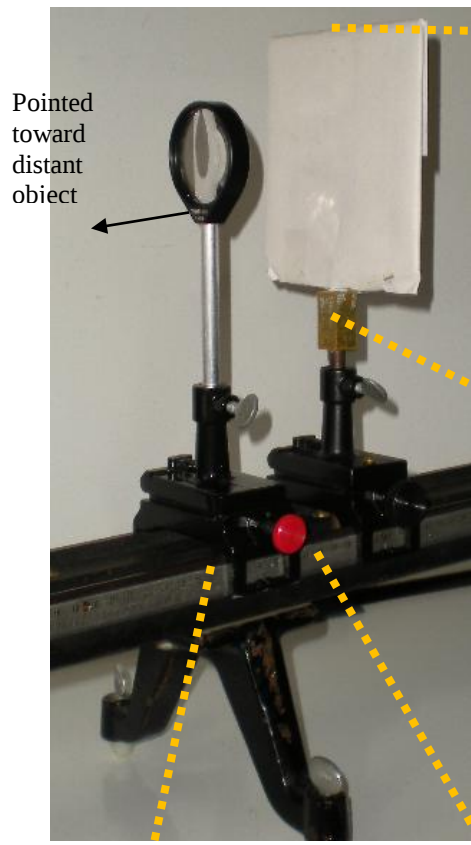


Figure 13.7 Use the converging lens, *not* the diverging lens, for Part I.

1. Measure the focal length by viewing a distant object

- Point the optical rail at a distant object. This object may be outside the building, at the opposite side of the room, or out in the hallway. For the purpose of this experiment, you can consider the distant object to be located at infinity.
- Mount the screen on the end of the rail opposite the object, and mount the lens between the screen and the object.
- Move the lens until the image is focused on the screen.
- Measure and record the image distance i . Refer to Figure 13.8 for details on making measurements with the optical rail.
- Use the thin lens formula to determine and record f .
- Displace the screen so that the image is no longer focused, then repeat the steps above for each partner.¹ Calculate the average value of f .
- Calculate the percent error of f from the manufacturer's value.

¹ We ask each partner to perform the same steps separately for two reasons. First, it makes sure that all partners are involved in the experiment, which in this experiment involve making measurements with the observer's eye, and second it will allow you to average results for each partner and thereby reduce random errors.



position indicator

Figure 13.8(a). Setup for measuring focal length using an image produced by a distant object.



Figure 13.8(b).
Lens mount.

The lens is mounted in a self-centering adapter, which positions the center of the lens directly above the position indicator.

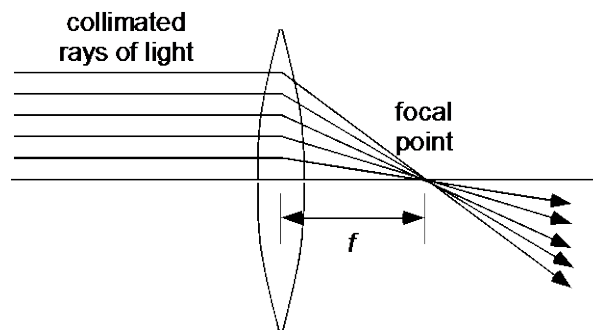


Figure 13.9. Ray tracing diagram, for procedures 1 and 2.

2. Test the thin lens formula with i and o both positive

- Install the illuminating object box (Figure 13.4) on the optical rail.
- Position the screen a distance $>4f$ from the object, using the value for f that you found in procedure 1. See Figure 13.10. (Hint: Position the object box at a position with a round number to make subtraction easier.)

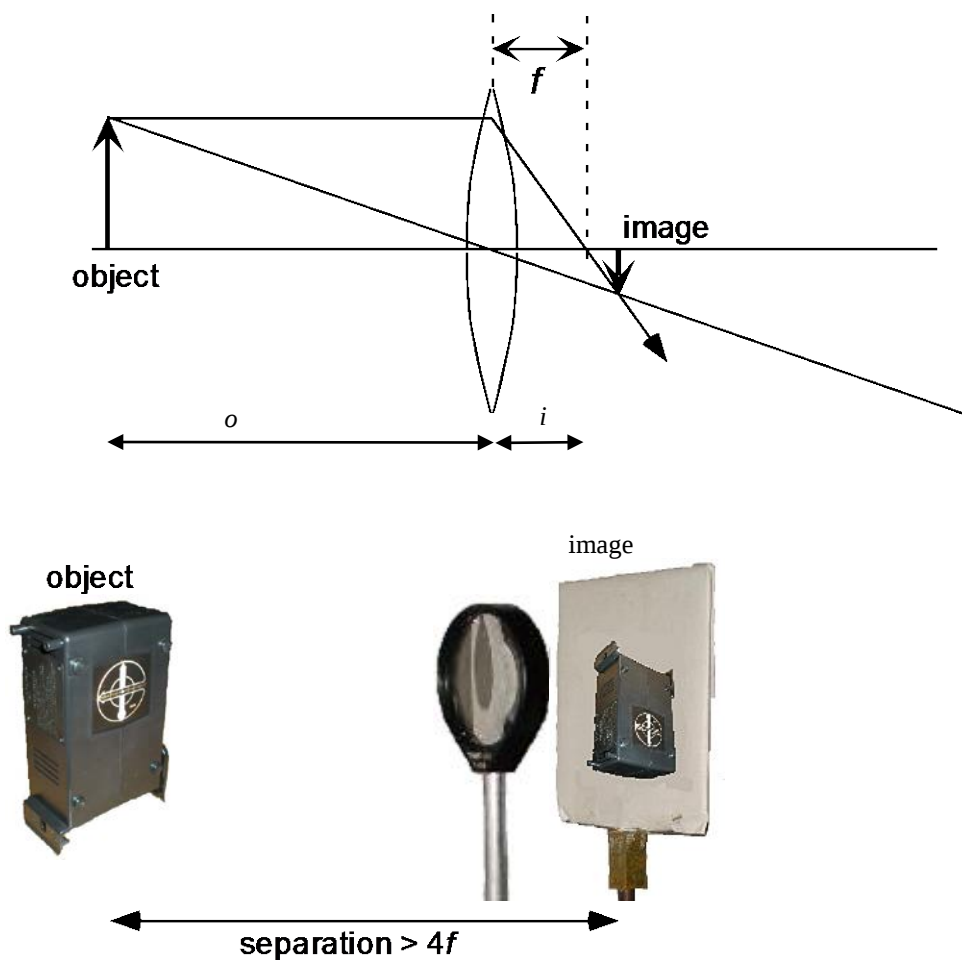


Figure 13.10. Setup for Part I, #2.

The ray-tracing diagram at the top corresponds to the components photographed at the bottom.

- Install the lens close to the object box, and adjust their heights to be the same, as shown in Figure 13.11.

- Move the lens position so that the image is focused. Measure and record o , i , h_o , and h_i . (Note that there are two such lens positions.)

- Find the other lens position that yields a focused image, and once again measure and record o , i , h_o , and h_i .

- Displace the lens so that the image is no longer focused. Repeat the steps above for each partner. Record the values measured by each partner, and then calculate the averages of the final results for all partners, as shown in the worksheet.

- Calculate f from Eq. (13.1) as indicated on the worksheet. Show your work in a **SAMPLE CALCULATION**.

- Compare your result to the manufacturer's value of f by calculating the percent error.

- Calculate the experimental magnification from Eq. (13.3) and the theoretical magnification from Eq. (13.4). Show your work in a **SAMPLE CALCULATION**.



Figure 13.11. Adjust the object box and lens to the same height.

3. Test the thin lens formula with i negative and o positive

Now we will create a virtual image of the illuminating object box. To make a virtual image with a converging lens, the object must be located close to the lens, so that $o < f$. See Figure 13.12(a). The complication in this procedure is measuring where the virtual image is located, as a virtual image cannot be displayed on a screen. We will exploit the fact that a telescope can focus on a virtual image just as well as on an actual object.

- Position the object box and the telescope on the rail about 60 cm apart. You will later create a virtual image at the current position of the light box.

- Focus the telescope so the light source is clear. Your telescope is now focused so that it can view anything at the current position of the object box, whether it be a physical object (like the light box is now), or a virtual image (as will be the case a couple bullets from now). See Figure 13.12(b).

- Insert the lens about halfway between the light source and the telescope. Measure the distance from the light source to the lens. When you create the virtual image in the next step, this distance will be i . Record this value on the worksheet as i . Remember; i will be negative as it will be a virtual image.

- While looking through the telescope, move the light source towards the lens until it is in focus.

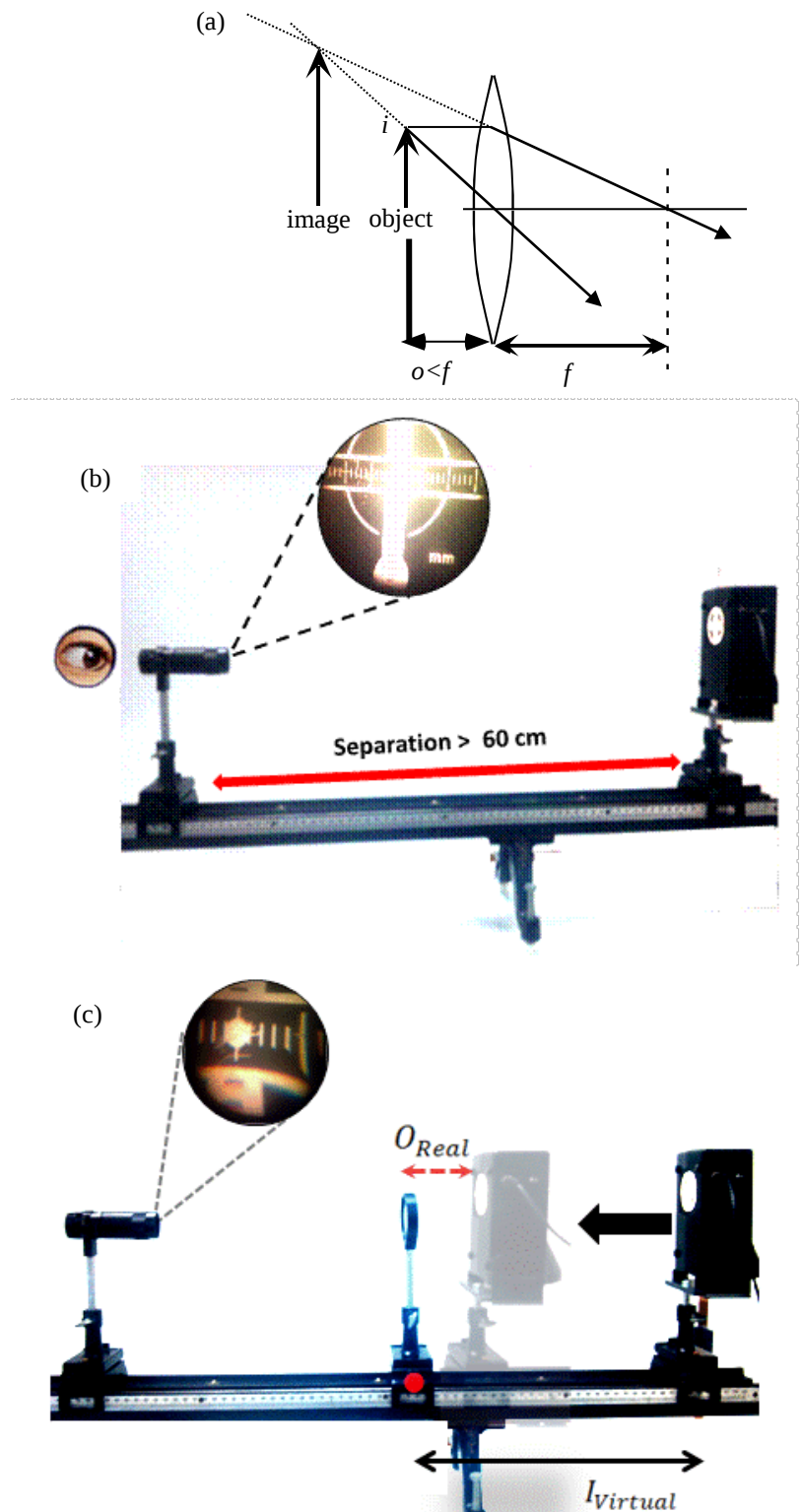


Figure 13.12. Setup for Part I, #3. The object is positioned near the lens, with $o < f$.

(a) Ray tracing diagram.

(b) You will view the light source through the telescope with the light source at the future location of the virtual image.

(c) You will insert the lens and position the box so it is in focus in the telescope. The light source position is now the location of the object.

Figures 13.12(b) and 3.12(c) by Maxim Perkhounkov.

Exp. A13: Thin Lenses

Now the light source is the object and so the distance between it and the lens is o . See Figure 13.12(c). Record o on your worksheet, remembering that o will be positive as it is a real object.

- Calculate f using the thin lens formula and your values of i and o . Notice that $o < f$, reinforcing the fact that we have just created a virtual image.
- Defocus the telescope. Repeat the steps above for each partner, recording a value for o and i and then f for each partner. Calculate an average value of f .
- Compare your result to the manufacturer's value of f by calculating a percent error.

Part II: Diverging Lens (i.e. Negative Lens with $f = -15\text{cm}$)

In this part of the experiment we determine the focal length of a diverging lens, comparing each time to the manufacturer's value of $f = -15\text{ cm}$.

1. Measure the focal length by viewing a distant object

In the following, o_d refers to the object of the diverging lens, i_d refers to the image of the diverging lens, o_c refers to the object of the converging lens, and i_c refers to the image for the converging lens. Set up the optical bench similarly to Figure 13.13 (See below). " i_c " must be greater than the focal length of the converging lens.

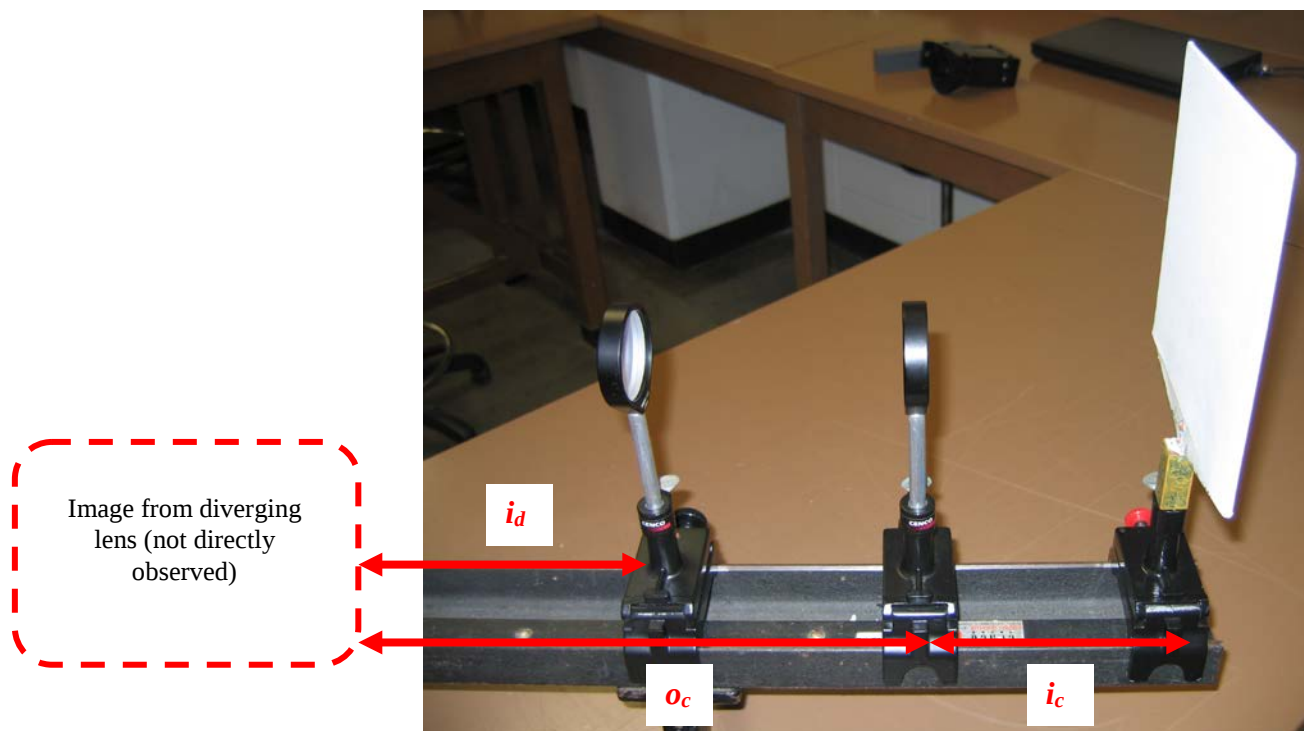


Figure 13.13: Setup for measuring the focal length of a diverging lens by viewing a distant object.

- Point the bench at something outside the window (or at the opposite end of the room if it is too dark outside).
- Move the screen to a position where the light coming through both lenses forms an image on the screen.
- Measure i_c . Using i_c and the manufacturer's value of the focal length for the converging lens, find o_c .
- Although you cannot directly observe the image from the diverging lens, you can still determine i_d . The important thing to notice here is that the image from the diverging lens is being used as the object for the converging lens. This means that $|i_d| = |o_c| - (\text{distance between lenses})$. See Figure 13.13.
- Determine the focal length of the diverging lens. (Hint: What is the value of o_d ?)
- Compare to the manufacturer's value of f by calculating a percent error.

Part III: Clean Up

- Turn off all equipment.
- Return all lenses to their proper storage container.
- Tidy the lab bench.
- Exit any running software.

Sample Calculations Summary

Part I: Converging lens

Page A13-10: Calculation of focal length

Page A13-10: Calculation of magnification

Analysis Questions

1. An image of a real object is being projected onto a screen through a single lens.
 - a. Is the lens converging or diverging? Why?
 - b. Is the image upright or inverted?
2. A single lens creates a virtual image of a real object. Is this enough information to determine if the lens is converging or diverging? If it is, say what kind of lens it is, and why. If it isn't enough information, explain why not.

