Introductory Physics

Laboratory Manual

Physics Department

The City College
of
The City University
of
New York

Contents

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Introduction

The aim of the laboratory exercise is to give the student an insight into the significance of the physical ideas through actual manipulation of apparatus, and to bring him or her into contact with the methods and instruments of physical investigation. Each exercise is designed to teach or reinforce an important law of physics which, in most cases, has already been introduced in the lecture and textbook. Thus the student is expected to be acquainted with the basic ideas and terminology of an experiment before coming to the laboratory.

The exercises in general involve measurements, graphical representation of the data, and calculation of a final result. The student should bear in mind that equipment can malfunction and final results may differ from expected values by what may seem to be large amounts. This does not mean that the exercise is a failure. The success of an experiment lies rather in the degree to which a student has:

- mastered the physical principles involved,
- understood the theory and operation of the instruments used, and
- realized the significance of the final conclusions.

The student should know well in advance which exercise is to be done during a specific laboratory period. The laboratory instructions and the relevant section of the text should be read before coming to the laboratory. All of the apparatus at a laboratory place is entrusted to the care of the student working at that place, and he or she is responsible for it. At the beginning of each laboratory period it is the duty of the student to check over the apparatus and be sure that all of the items listed in the instructions are present and in good condition. Any deficiencies should be reported to the instructor immediately.

The procedure in each of these exercises has been planned so that it is possible for the prepared student to perform the experiment in the scheduled laboratory period. Data sheets should be initialed by your instructor or TA. Each student is required to submit a written report which presents the student's own data, results and the discussion requested in the instructions. Questions that appear in the instructions should be thought about and answered at the corresponding position in the report. Answers should be written as complete sentences.

If possible, reports should be handed in at the end of the laboratory period. However, if this is not possible, they must be submitted no later than the beginning of the next exercise OR the deadline set by your instructor.

Reports will be graded, and when possible, discussed with the student. You may check with the TA about your grade two weeks after you have submitted it.

Laboratory Manners

1. Smoking is not permitted in any college building.
2. Students must not bring food or drinks into the room.
3. Apparatus should not be taken from another position. If something is missing, notify the instructor, and either equipment will be replaced or appropriate adjustments will be made.
4. Students should be distributed as evenly as possible among the available positions. Generally, no more than two students should be working together.
5. At the end of the period the equipment should left neatly arranged for the next class. Non-functioning equipment should be reported before leaving. All papers and personal items have to be removed.

Measurements and Uncertainty

> "A measurement result is complete only when accompanied by a quantitative statement of its uncertainty. The uncertainty is required in order to decide if the result is adequate for its intended purpose and to ascertain if it is consistent with other similar results."
> National Institute of Standards and Technology

1. Introduction

No measuring device can be read to an unlimited number of digits. In addition when we repeat a measurement we often obtain a different value because of changes in conditions that we cannot control. We are therefore uncertain as to the exact values of measurements. These uncertainties make quantities calculated from such measurements uncertain as well.

Finally we will be trying to compare our calculated values with a value from the text in order to verify that the physical principles we are studying are correct. Such comparisons come down to the question "Is the difference between our value and that in the text consistent with the uncertainty in our measurements?".

The topic of measurement involves many ideas. We shall introduce some of them by means of definitions of the corresponding terms and examples.

Sensitivity - The smallest difference that can be read or estimated on a measuring instrument. Generally a fraction of the smallest division appearing on a scale. About 0.5 mm on our rulers. This results in readings being uncertain by at least this much.

Variability - Differences in the value of a measured quantity between repeated measurements. Generally due to uncontrollable changes in conditions such as temperature or initial conditions.

Range - The difference between largest and smallest repeated measurements. Range is a rough measure of variability provided the number of repetitions is large enough. Six repetitions are reasonable. Since range increases with repetitions, we must note the number used.

Uncertainty - How far from the correct value our result might be. Probability theory is needed to make this definition precise, so we use a simplified approach.

We will take the larger of range and sensitivity as our measure of uncertainty.

Example: In measuring the width of a piece of paper torn from a book, we might use a cm ruler with a sensitivity of 0.5 mm (0.05 cm), but find upon 6 repetitions that our measurements range from 15.5 cm to 15.9 cm. Our uncertainty would therefore be 0.4 cm.

Precision - How tightly repeated measurements cluster around their average value. The uncertainty described above is really a measure of our precision.

Accuracy - How far the average value might be from the "true" value. A precise value might not be accurate. For example: a stopped clock gives a precise reading, but is rarely accurate. Factors that affect accuracy include how well our instruments are calibrated (the correctness of the marked values) and how well the constants in our calculations are known. Accuracy is affected by systematic errors, that is, mistakes that are repeated with each measurement.

Example: Measuring from the end of a ruler where the zero position is 1 mm in from the end.

Blunders - These are actual mistakes, such as reading an instrument pointer on the wrong scale. They often show up when measurements are repeated and differences are larger than the known uncertainty. For example: recording an 8 for a 3, or reading the wrong scale on a meter..

Comparison - In order to confirm the physical principles we are learning, we calculate the value of a constant whose value appears in our text. Since our calculated result has an uncertainty, we will also calculate a Uncertainty Ratio, UR, which is defined as

$$\mathrm{UR} = \frac{|\text{experimental value} \ - \ \text{text value}|}{\text{Uncertainty}}$$

A value less than 1 indicates very good agreement, while values greater than 3 indicate disagreement. Intermediate values need more examination. The uncertainty is not a limit, but a measure of when the measured value begins to be less likely. There is always some chance that the many effects that cause the variability will all affect the measurement in the same way.

Example: Do the values 900 and 980 agree?
If the uncertainty is 100 , then $UR = 80/100 = 0.8$ and they agree,
but if the uncertainty is 20 then $UR = 80/20 = 4$ and they do not agree.

2. Combining Measurements

Consider the simple function $R = a\,b$ when a and b have uncertainties of Δa and Δb. Then

$$\Delta R = (a + \Delta a)(b + \Delta b) - a\,b = a\,\Delta b + b\,\Delta a + (\Delta b)(\Delta a)$$

Since uncertainties are generally a few percent of the value of the variables, the last product is much less than the other two terms and can be dropped. Finally, we note that dividing by the original value of R separates the terms by the variables.

$$\frac{\Delta R}{R} = \frac{\Delta a}{a} + \frac{\Delta b}{b}$$

The RULE for combining uncertainties is given in terms of fractional uncertainties, $\Delta x/x$. It is simply that each factor contributes equally to the fractional uncertainty of the result.

Example: To calculate the acceleration of an object travelling the distance d in time t, we use the relationship: $a = 2\,d\,t^{-2}$. Suppose d and t have uncertainties Δd and Δt, what is the resulting uncertainty in a, Δa?

Note that t is raised to the second power, so that $\Delta t/t$ counts twice. Note also that the numerical factor is the absolute value of the exponent. Being in the denominator counts the same as in the numerator. The result is that

$$\frac{\Delta a}{a} = \frac{\Delta d}{d} + 2\frac{\Delta t}{t}$$

Examination of the individual terms often indicates which measurements contribute the most to the uncertainty of the result. This shows us where more care or a more sensitive measuring instrument is needed.

If $d = 100$ cm, $\Delta d = 1$ cm, $t = 2.4$ s and $\Delta t = 0.2$ s, then $\Delta d/d = (1\text{cm})/(100\text{cm}) = 0.01 = 1\%$ and $2\Delta t/t = 2(0.2\text{s})/(2.4\text{s}) = 0.17 = 17\%$. Clearly the second term controls the uncertainty of the result. Finally, $\Delta a/a = 18\%$. (As you see, fractional uncertainties are most compactly expressed as percentages, and since they are estimates, we round them to one or two meaningful digits.)

Calculating the value of a itself $(2 \times 100/2.4^2)$, the calculator will display 34.7222222. However, it is clear that with $\Delta a/a = 18\%$ meaning $\Delta a \approx 6$ cm s^{-2}, most of those digits are meaningless. Our result should be rounded to 35 cm s^{-2} with an uncertainty of 6 cm s^{-2}.

In recording data and calculations we should have a sense of the uncertainty in our values and not write figures that are not significant. Writing an excessive number of digits is incorrect as it indicates an uncertainty only in the last decimal place written.

3. A General Rule for Significant Figures

In multiplication and division we need to count significant figures. These are just the number of digits, starting with the first non-zero digit on the left. For instance: 0.023070 has five significant figures, since we start with the 2 and count the zero in the middle and at the right.

The rule is: Round to the factor or divisor with the fewest significant figures. This can be done either before the multiplication or division, or after.

Example: $7.434 \times 0.26 = 1.93284 = 1.9$ (2 significant figures in 0.26).

4. Reporting Uncertainties

There are two methods for reporting a value V, and its uncertainty U.

A. The technical form is "$(V \pm U)$ units".

Example: A measurement of 7.35 cm with an uncertainty of 0.02 cm would be written as (7.35 ± 0.02) cm. Note the use of parentheses to apply the unit to both parts.

B. Commonly, only the significant figures are reported, without an explicit uncertainty. This implies that the uncertainty is 1 in the last decimal place.

Example: Reporting a result of 7.35 cm implies ± 0.01 cm.

Note that writing 7.352786 cm when the uncertainty is really 0.01 cm is wrong.

C. A special case arises when we have a situation like 1500 ± 100. Scientific notation allows use of a simplified form, reporting the result as 1.5×10^3. In the case of a much smaller uncertainty, 1500 ± 1, we report the result as 1.500×10^3, showing that the zeros on the right are meaningful.

5. Additional Remarks

A. In the technical literature, the uncertainty also called the error.

B. When measured values are in disagreement with standard values, physicists generally look for mistakes (blunders), re-examining their equipment and procedures. Sometimes a single measurement is clearly very different from the others in a set, such as reading the wrong scale on a clock for a single timing. Those values can be ignored, but NOT erased. A note should be written next to any value that is ignored.

Given the limited time we will have, it will not always be possible to find a specific cause for disagreement. However, it is useful to calculate at least a preliminary result while still in the laboratory, so that you have some chance to find mistakes.

C. In adding the absolute values of the fractional uncertainties, we overestimate the total uncertainty since the uncertainties can be either positive or negative. The correct statistical rule is to add the fractional uncertainties in quadrature, i.e.

$$\left(\frac{\Delta y}{y}\right)^2 = \left(\frac{\Delta a}{a}\right)^2 + \left(\frac{\Delta b}{b}\right)^2$$

D. The professional method of measuring variation is to use the Standard-Deviation of many repeated measurements. This is the square root of the total squared deviations from the mean, divided by the square root of the number of repetitions. It is also called the Root-Mean-Square error.

E. Measurements and the quantities calculated from them usually have units. Where values are tabulated, the units may be written once as part of the label for that column The units used must appear in order to avoid confusion. There is a big difference between 15 mm, 15 cm and 15 m.

Graphical Representation of Data

Graphs are an important technique for presenting scientific data. Graphs can be used to suggest physical relationships, compare relationships with data, and determine parameters such as the slope of a straight line.

There is a specific sequence of steps to follow in preparing a graph. (See Figure 1)

1. Arrange the data to be plotted in a table.

2. Decide which quantity is to be plotted on the x-axis (the abscissa), usually the independent variable, and which on the y-axis (the ordinate), usually the dependent variable.

3. Decide whether or not the origin is to appear on the graph. Some uses of graphs require the origin to appear, even though it is not actually part of the data, for example, if an intercept is to be determined.

4. Choose a scale for each axis, that is, how many units on each axis represent a convenient number of the units of the variable represented on that axis. (Example: 5 divisions = 25 cm)

   Scales should be chosen so that the data span almost all of the graph paper, and also make it easy to locate arbitrary quantities on the graph. (Example: 5 divisions = 23 cm is a poor choice.) Label the major divisions on each axis.

5. Write a label in the margin next to each axis which indicates the quantity being represented and its units.

   Write a label in the margin at the top of the graph that indicates the nature of the graph, and the date the data were collected. (Example: "Air track: Acceleration vs. Number of blocks, 12/13/05")

6. Plot each point. The recommended style is a dot surrounded by a small circle. A small cross or plus sign may also be used.

7. Draw a smooth curve that comes reasonably close to all of the points. Whenever possible we plot the data or simple functions of the data so that a straight line is expected.

   A transparent ruler or the edge of a clear plastic sheet can be used to "eyeball" a reasonable fitting straight line, with equal numbers of points on each side of the line. Draw a single line all the way across the page. Do not simply connect the dots.

8. If the slope of the line is to be determined, choose two points on the line whose values are easily read and that span almost the full width of the graph. These points should not be original data points.

   Remember that the slope has units that are the ratio of the units on the two axes.

9. The uncertainty of the slope may be estimated as the larger uncertainty of the two end points, divided by the interval between them.

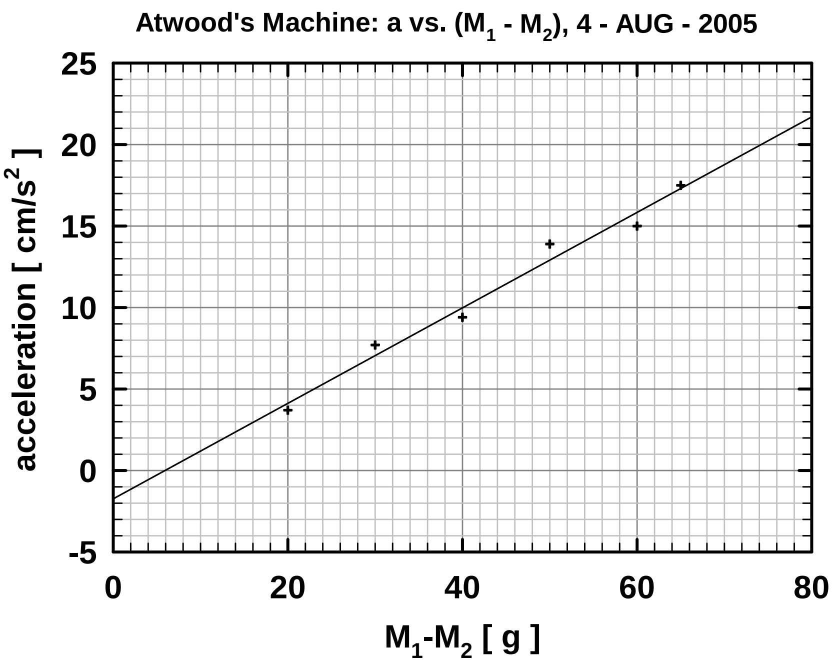


Figure 1: Example graph.

Using Figure 1 as an example, the slope of the straight line shown may be calculated from the values at the left and right edges, (-1.8 cm/s^{-}2 at 0 g and 21.8 cm/s^2 at 80 g) to give the value:

$$\text{Slope} = \frac{(21.8 - (-1.8))\ \text{cm/s}^2}{(80 - 0)\ \text{g}} = \frac{23.6\ \text{cm/s}^2}{80\ \text{g}} = 0.295 \frac{\text{cm}}{\text{s}^2\ \text{g}}$$

Suppose that the uncertainty is about 1.0 cm/s^2 at the 70 g value. The uncertainty in the slope would then be (1.0 cm/s^2)/(70 - 20) g = 0.02 cm/(s^2 g). We should then report the slope as (0.30 ± 0.02) cm/(s^2 g). (Note the rounding to 2 significant figures.)

If the value of g (the acceleration of free fall) in this experiment is supposed to equal the slope times 3200 g, then our experimental result is

$$3200\ \text{g} \times (0.30 \pm 0.02)\ \text{cm/(s}^2\ \text{g)} = (9.60 \pm 0.64)\ \text{m/s}^2$$

To compare with the standard value of 9.81 m/s^2, we calculate the uncertainty ratio, UR.

$$\text{UR} = (9.81 - 9.60)/0.64 = 0.21/0.64 = 0.33,$$

so the agreement is very good.

[Note: Making the uncertainty too large (lower precision) can make the result appear in better agreement (seem more accurate), but makes the measurement less meaningful.]

The Vernier Caliper

A vernier is a device that extends the sensitivity of a scale. It consists of a parallel scale whose divisions are less than that of the main scale by a small fraction, typically 1/10 of a division. Each vernier division is then 9/10 of the divisions on the main scale. The lower scale in Fig. 2 is the vernier scale, the upper one, extending to 120 mm is the main scale.

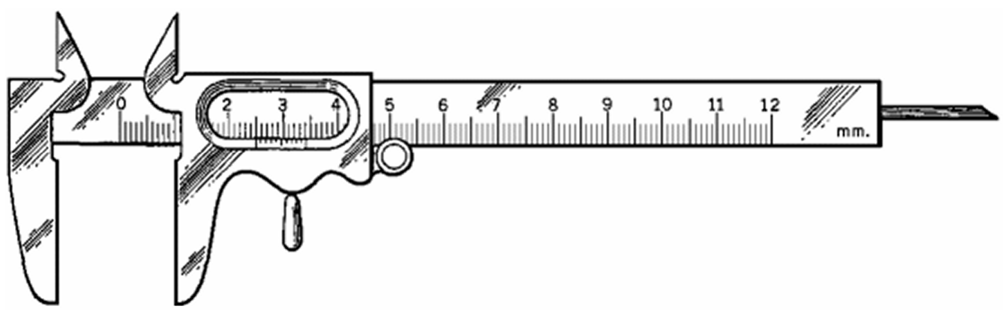
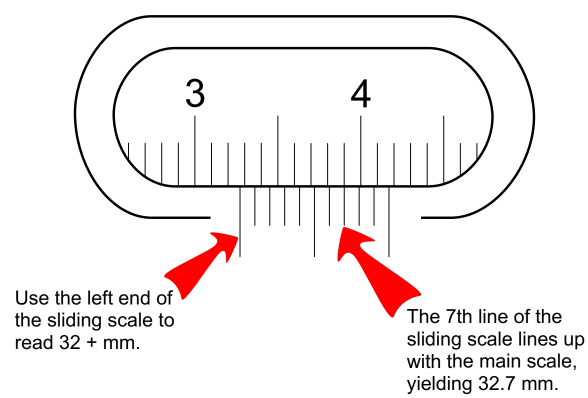


Figure 2: Vernier Caliper.

The left edge of the vernier is called the index, or pointer. The position of the index is what is to be read. When the index is beyond a line on the main scale by 1/10 then the first vernier line after the index will line up with the next main scale line. If the index is beyond by 2/10 then the second vernier line will line up with the second main scale line, and so forth.



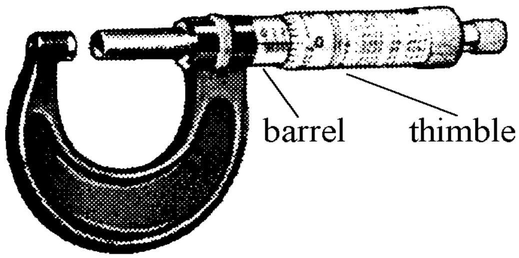
If you line up the index with the zero position on the main scale you will see that the ten divisions on the vernier span only nine divisions on the main scale. (It is always a good idea to check that the vernier index lines up with zero when the caliper is completely closed. Otherwise this zero reading might have to be subtracted from all measurements.)

Note how the vernier lines on either side of the matching line are inside those of the main scale. This pattern can help you locate the matching line.

The sensitivity of the vernier caliper is then 1/10 that of the main scale. Keep in mind that the variability of the object being measured may be much larger than this. Also be aware that too much pressure on the caliper slide may distort the object being measured.

The Micrometer Caliper

Also called a screw micrometer, this measuring device consists of a screw of pitch 0.5 mm and two scales, as shown in Fig. 3. A linear scale along the barrel is divided into half millimeters, and the other is along the curved edge of the thimble, with 50 divisions.



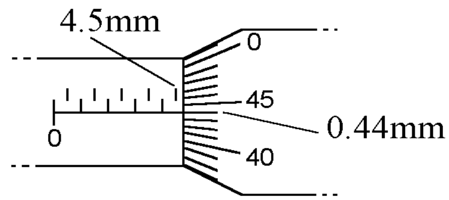


Figure 3: Micrometer Caliper.

The pointer for the linear scale is the edge of the thimble, while that for the curved scale is the solid line on the linear scale. The reading is the sum of the two parts in mm . The divisions on the linear scale are equal to the pitch, 0.5 mm. Since this corresponds to one revolution of the thimble, with its 50 divisions, then each division on the thimble corresponds to a linear shift of (0.50 mm)/50 = 0.01 mm .

In Fig. 3, the value on the linear scale can be read as 4.5 mm , and the thimble reading is 44×0.01 mm = 0.44 mm. The reading of the micrometer is then (4.50 + 0.44) mm = 4.94 mm.

Since a screw of this pitch can exert a considerable force on an object between the spindle and anvil, we use a ratchet at the end of the spindle to limit the force applied and thereby, the distortion of the object being measured. The micrometer zero reading should be checked by using the ratchet to close the spindle directly on the anvil. If it is not zero, then this value will have to be subtracted from all other readings.

Angle Scale Verniers

This type of vernier appears on spectrometers, where a precise measure of angle is required. Angles arc measured in degrees (°) and minutes ('), where 1 degree = 60 minutes. Fig. 4 shows an enlarged view of a typical spectrometer vernier, against a main scale which is divided in 0.5° = 30'.

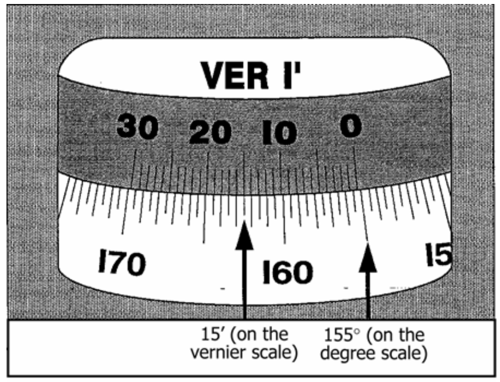


Figure 4: Angle Scale Vernier.

The Vernier has 30 divisions, so that the sensitivity of the vernier is one minute. (There are also two extra divisions, one before 0 and the other after 30, to assist in checking for those values.) Each division on the vernier is by 1/30 smaller than the division of the main scale. When the index is beyond a main scale line by 1/30 of a division or 1', line 1 on the vernier is lined up with the next main scale line. When that difference is 2/30 or 2', line 2 on the vernier lines up with the next line on the main scale, and so on.

Fig. 4 shows an example where degree and Vernier scale run from right to left. Again, reading the angle is a two step process. First we note the position of the index (zero line on the Vernier) on the main scale. In the figure it is just beyond 155.0°. To read the vernier, we note that line 15 seems to be the best match between a vernier line and a main scale line. The reading is then $155.0° + 15' = 155°\,15' = 155.25°$.

The example shows one problem with working with angles, the common necessity of converting between decimal fraction and degree-minute-second (DMS) notation. We illustrate another place where this arises with the problem of determining the angle between the direction of light entering the spectrometer, and the telescope used to observe light of a particular wavelength.
<u>Example:</u> The position of the telescope to observe the zeroth diffraction order is $121°55'$. Light of a certain wavelength is observed at $138°48'$. The steps in the subtraction are illustrated below, using DMS and decimal notation, respectively. Either method is correct.

	DMS	decimal
$138°\,48'$	$137°\,108'$	$138.80°$
$-\ 121°\,55'$	$-\ 121°\ \ 55'$	$-\ 121.92°$
?????	$16°\ \ 53'$	$16.88°$

Introduction to the Oscilloscope

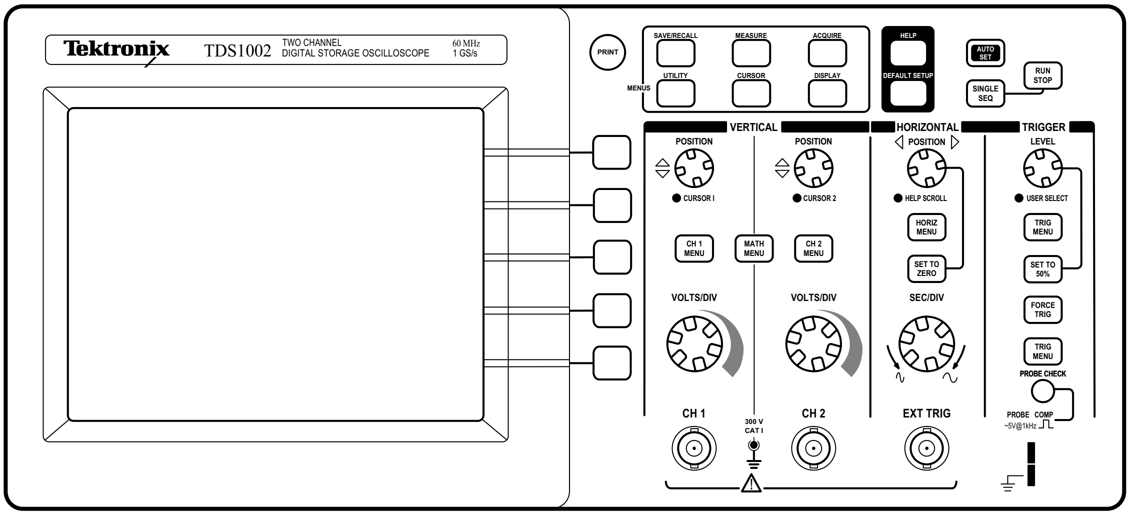


Figure 1: Front view of the oscilloscope TDS1002

Fig. 1 shows the front view of the oscilloscope TEKTRONIX TDS1002. Besides the display, the electronics of an oscilloscope can be divided into 3 major units:

1. amplifier (VERTICAL)
2. time base (HORIZONTAL)
3. trigger unit (TRIGGER)

The time base determines at which speed the input signal is detected (sampled). The amplifier prepares and samples the input signal at the rate given by the time base. The trigger unit is used to choose the event at which the amplifier starts to record the signal. Mostly, this is an edge (low-high or high-low) of the sampled waveform, but one can also trigger on more sophisticated events (pulses of a pre-defined duration, a number of edges within a given time etc.).

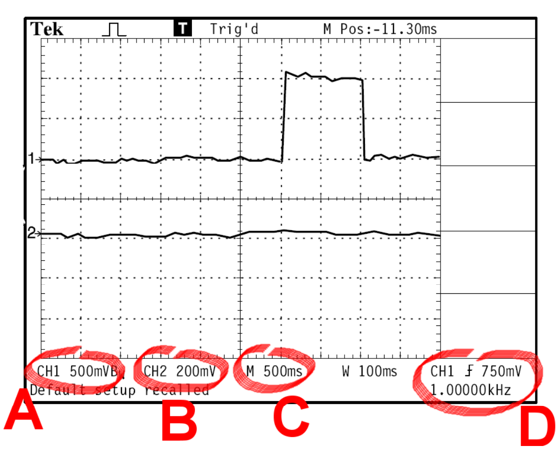


Figure 2: Screenshot

The display (Fig. 2) is covered by a graticule, the distance between two adjacent lines is called a division. With the SEC/DIV and VOLTS/DIV knob the corresponding time (horizontal) and voltage (vertical) scaling of both these axes can be adjusted. All of these settings as well as the functions that are assigned to the programmable buttons on the right side of the screen are displayed on the screen.

Setting the horizontal axis

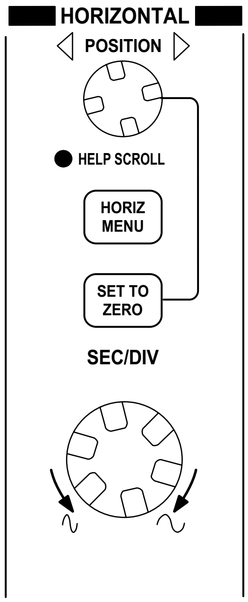


Figure 3: Horizontal settings

With this part (Fig. 3), one determines the time window for which the voltage waveform is displayed. The setting is changed with the SEC/DIV dial, settings range from 5 ns per division (turning the dial clockwise) to 50 s per division (turning it counter-clockwise). The chosen value is displayed on the screen (Part C of Fig. 2). With the POSITION dial, the waveform can be shifted horizontally. If we expect to observe a signal with a frequency f, the time scale should be chosen to be close to $1/(n \times f)$, where n is the number of divisions that one period of the signal is supposed to occupy.
Example: To display a 250 Hz signal in 9 divisions (almost filling the whole screen), we calculate the setting as $1/(9 \times 250Hz) = 440\mu$s/div. The available settings are 250 μs and 500 μs per division. Starting with the larger value will result in one cycle occupying (4 ms)/(0.5 ms/div) = 8 div.

Setting the vertical axis

To get a signal onto the screen, we have to connect the leads to one of the amplifier channels. The leads usually have an outer shield, which is grounded and has black insulation. This wire must be connected to the GROUND side of the signal source. The appropriate channel has to be displayed, which can be toggled by pressing the CH1 MENU or CH2 MENU button in the VERTICAL section of the front panel (Fig. 4). On the screen (Part A and B of Fig. 2), you see which channels are active and what is the voltage setting for either of them. This setting can be changed by turning the VOLTS/DIV dial, values reaching from 2 mV/DIV (fully clockwise) to 5 V/DIV (fully counter-clockwise) are available.

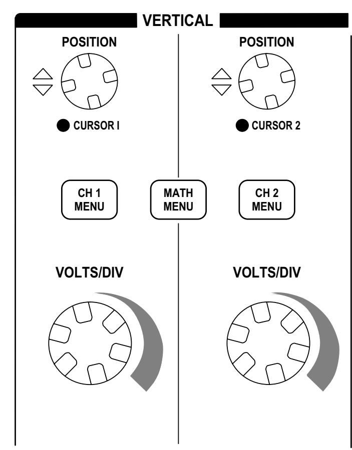


Figure 4: Vertical settings

The voltage offset (i.e. the vertical position of the waveform with the respect to the middle line) can be adjusted by rotating the POSITION dial. Also, if CH1 MENU or CH2 MENU are pressed, a menu is displayed on the right side of the screen, that determines several features of the respective vertical amplifier. Settings should be: Coupling: AC, BW Limit: Off, Volts/Div: Coarse, Probe: 1x, Invert: Off. When measuring signal amplitudes, the value read from the screen must be multiplied with the setting displayed on the screen.

Example: A 3.2 division amplitude on the screen would represent 6.4 V at a setting of 2.00 V/div but only 320 mV at 100 mV/div.

Synchronizing the display

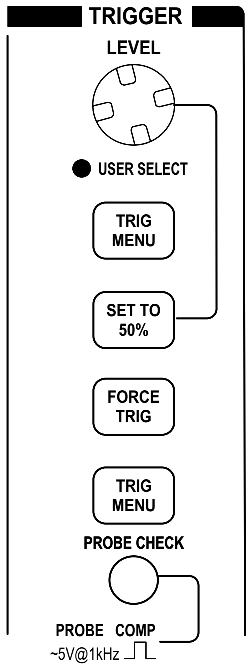


Figure 5: Trigger settings

In order to obtain a stable display of a periodic signal, the sweep must begin at the same point in each signal cycle. There are a set of TRIGGER controls at the right side of the front panel (Fig. 5) that select how this is to be accomplished. By pressing the button TRIG MENU you enter the trigger menu, displayed on the right side of the screen. Use the settings: Type: Edge, Slope: Rising, Mode: Auto, Coupling: DC. Source can be set to CH1 or CH2, according to where the signal is connected. The latter setting as well as trigger level (voltage) and type are displayed on the screen (Part D of Fig. 2).

With the knob TRIGGER LEVEL, the voltage at which the display of the waveform starts, is adjusted. The trigger level is displayed as a small horizontal arrow in the rightmost division on the screen. This level should be kept as near to the center position as possible, but adjusted slightly in order to obtain a stationary display. You may have to readjust the Trigger Level when the amplification is changed or when the signal significantly changes.

Working with the INSTEK Signal Generator

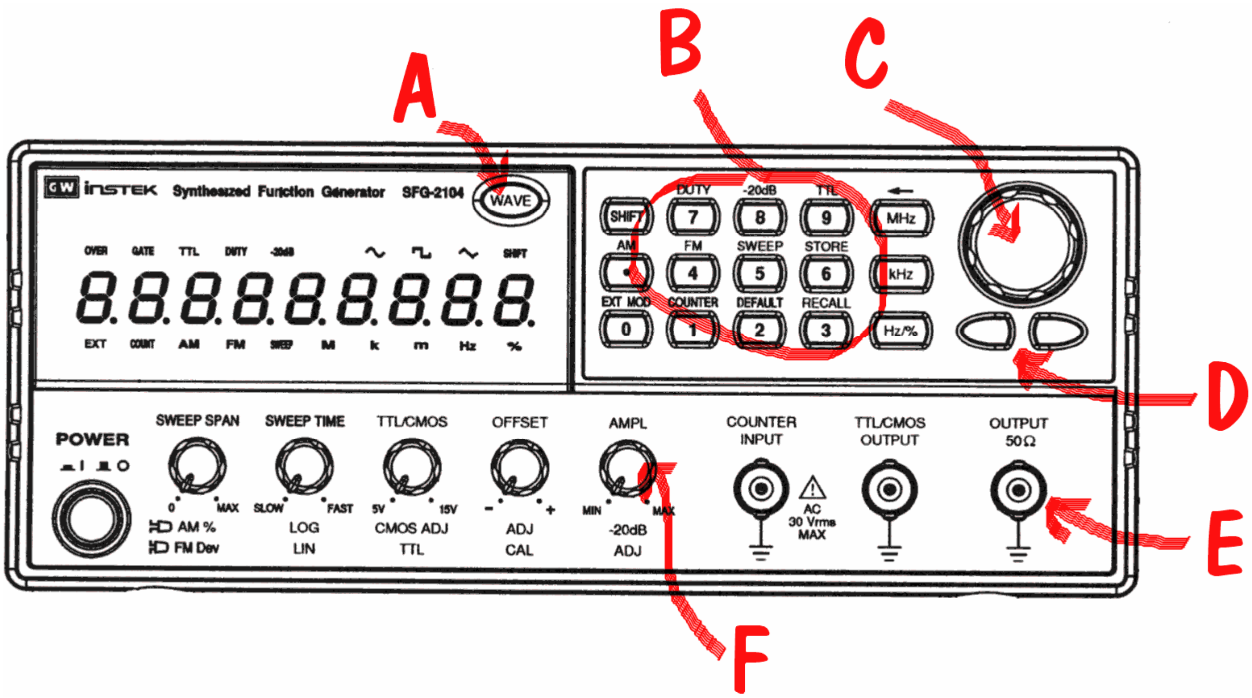


Figure 6: Front Panel of the Signal Generator

Don't be confused by the large number of buttons on the front panel, you will only use a few of them. The output voltage of the waveform generator is connected to the circuit with a BNC-adapter at outlet E. For the experiments, waveform, frequency, and voltage have to be adjusted.

Choosing the waveform

With the "WAVE"-button (item A in Fig. 6), one can toggle between triangular, rectangular, and sine wave as an output. The choice is displayed directly below this button.

Setting the frequency

The output frequency of the generator can be set in two ways:

- Direct input via the keypad (item B of Fig. 6), type the number and enter the value by pressing the appropriate unit (Hz, kHz, or MHz).
- If a value is already entered and displayed, each single digit can be changed separately. With the two keys (item D of Fig. 6), the active digit is selected, it is blinking a few seconds after the selection. Then, with knob C, the digit can be changed, wait at least one second, until the change becomes active at the output.

Setting the amplitude

The output voltage is continuously variable with knob F.

Air Track

APPARATUS

1. Air Track with air blower
2. Glider with spring bumpers
3. Stop clock
4. Set of four 1.27 cm thick spacers
5. Meter stick (and vernier caliper)

INTRODUCTION

The air track is a long hollow aluminum casting with many tiny holes in the surface. Air blown out of these holes provides an almost frictionless cushion of air on which the glider can move. The air track and gliders operate best if they are clean and smooth. If their surfaces are dirty or show bumps or nicks, inform your instructor before proceeding. Dirt, bumps, and nicks can result in scratching the surfaces of the track and glider. To avoid scratching, use care in handling the apparatus. The most important rule is this: *at no time should the glider be placed on the air track if the blower is not in operation.*

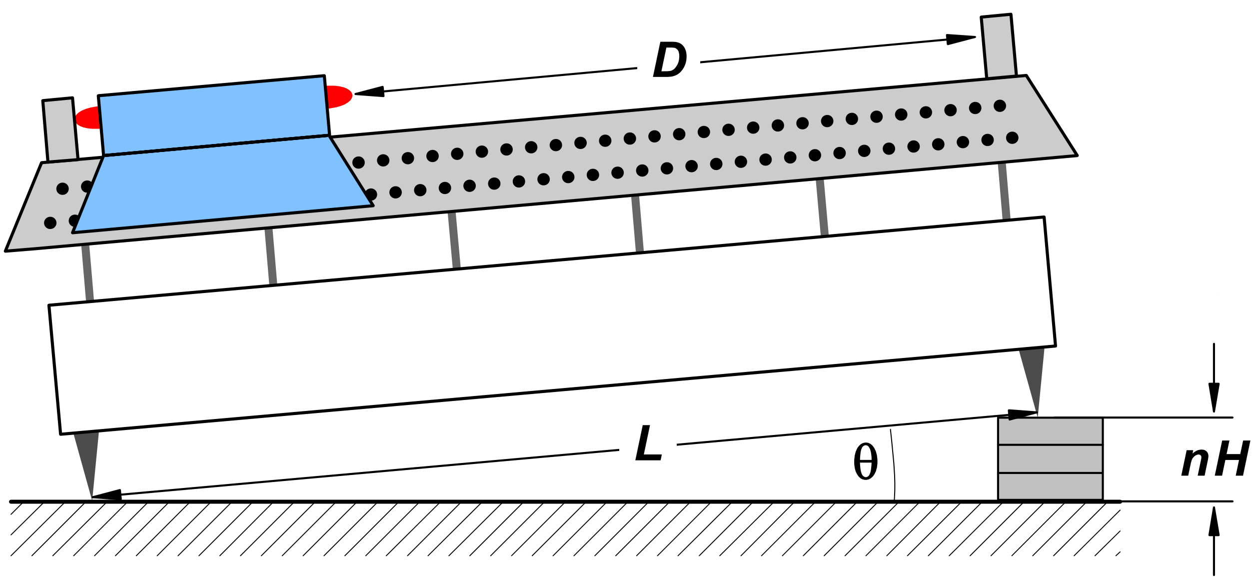


Figure 1: Air Track with dimensions.

The air track, with air blowing, serves as an almost frictionless surface. When one end is raised, it becomes a frictionless inclined plane (see Fig. 1). According to theory, the acceleration a of an object due to gravity down a frictionless incline of angle θ is $a = g\ sin\,\theta$. The main idea of this experiment is two-fold: first, to check that the acceleration is proportional to $sin\,\theta$, and second, to find the value of g, the acceleration of free fall.

The acceleration down the track is to be found for each of four incline angles by measuring the time t required for the glider to slide the measured distance D down the length of the track, and, using the formula $D = \frac{1}{2}\,a\,t^2$, to get $a = 2\,D/t^2$ (see Fig. 1).

The collision between the glider and the spring bumper at the bottom of the track is not perfectly elastic, that is, the glider rebounds at lower speed and less kinetic energy than it had just before the collision. This is demonstrated by the fact that the glider rebounds a distance $D' < D$. The potential energy of the glider with respect to the bottom of the track just before release is $m\ g\ D\ sin\,\theta$, while the potential energy at standstill after rebound is $m\ g\ D'\ sin\,\theta$. These are also the kinetic energies just immediately before (K) and immediately after (K') the collision, respectively. The fractional loss of energy is then: $(K - K')/K = 1 - (K'/K) = 1 - (D'/D)$.

PROCEDURE

Part A: Determining the acceleration

1. Check that the air track is level (horizontal). It should take the glider at least 10 seconds to move across the track, no matter at which end it is placed. If it is not sufficiently level check with your instructor.

2. Measure:

   a) The distance D the glider moves in going from one end of the track to the other.
   b) The distance L between the base supports of the air track.

3. Place one spacer under the single track support. With the air on, place the glider at the upper end with about one millimeter gap between the glider and the stationary spring. Take a few practice timings to get used to starting the clock at the time the glider is released, and stopping the clock when it hits the spring at the lower end.
   Be careful when reading the clock. The two dials have different divisions.
   When you are used to the process of release and timing, then proceed.

4. Set up a table with the headings shown below:

n (# of blocks)	t_1 (s)	t_2 (s)	$t_{average}(s)$	a (m/s^2)
1				
2				

   Be sure to indicate the units used. For each value of n, from 1 to 4, measure the time twice. If they differ by more than 5%, then take another pair of times. Continue until two successive times are within 5%.

5. With four blocks in place, $n = 4$, take a total of six times. We will use this information to determine the variability in our time measurements.

Part B: Determining the dissipated energy

1. With two spacers, measure the rebound distance D'. Use the average of two successive measurements that are within 5% of each other.

2. Evaluate the fraction of the original kinetic energy that is lost in the collision.

3. Explain the equations relating K and K' to D and D' and then derive $K'/K = D'/D$.

ANALYSIS

1. If friction has been eliminated, what are the forces exerted on the glider?
   Draw the Free Body Diagram of the glider.
   Find the net force and apply Newton's Second Law to determine the algebraic relation between the acceleration a, g and the angle θ of the track.
   Use the fact that $sin\,\theta = n\ H/L$ to express a in terms of n algebraically.
   What kind of a graph would you expect for a vs. n?

2. Review the material in the introduction to the lab manual on graphing, and using graphs. Select scales so that the graph of a vs. n takes up most of the page. Do include the origin. Plot your data points. Draw the single straight line that best fits your data points. Determine the slope of that line by using two widely separated points on the line that are not data points. What are the units of the slope?

3. Use the analysis of step 2 to relate your value of the slope to g. Determine g from your slope.

4. In order to compare your value of g with the standard value, a value for the experimental uncertainty is needed. Review the material in the introduction on "Measurements and Uncertainty" and on using graphs. Determine the range of the six times measured for $n = 4$. Take this value as the uncertainty in time measurements, Δt. Determine the uncertainty in the value of acceleration Δa due to Δt. The uncertainly in the slope measurement is just Δa divided by the range of n. Finally, determine Δg from the relation between g and the slope.

5. Compare your value with the standard value by calculating the Uncertainty Ratio:

   $$\frac{|g - g_{standard}|}{\Delta g}$$

   Values less than 1 indicate excellent agreement, greater than 4, disagreement and possible mistakes. Values between 1 and 4 are ambiguous, indicating fair or poor agreement. How well does your result agree with the standard value?

Atwood's Machine

APPARATUS

1. The apparatus consists of two composite masses connected by a flexible wire that runs over two ball-bearing pulleys. The make up of the composite masses at the beginning of the experiment is:

	Left Side	Right Side
	1×1 g	
	2×2 g	
	4×5 g	
	1×10 g	
	1×250 g	1×250 g
	1×500 g	1×500 g
	1×965 g	1×1000 g
Total mass:	1750 g	1750 g

2. Stop clock
3. Pair of tweezers
4. Ruler

INTRODUCTION

This Atwood's machine consists essentially of a wire passing over a pulley with a cylindrical mass attached to each end of the string, The cylinders are composed of three sections, the lower ones of 250 g, and the middle ones of 500 g. Note that the two top-most sections (the sections to which the wire is tied) , do not have the same mass. The one on the left has a mass of 965 g. The right hand one has a mass of 1000 g. Each of these sections has eight vertical holes drilled into its top. When all the small masses are in the left cylinder, the two cylinders have the same mass and the force $(M_1 - M_2)g = 0$. In other words, there is no unbalanced force and the system remains at rest when the brake is released the 10 g mass is transferred from the left to the right hand cylinder, the difference between the two masses becomes $(M_1 - M_2) = 20$ g, while the sum $(M_1 + M_2)$ remains unchanged. If now an additional 5 g mass is transferred, the mass difference becomes 30 g, while the sum is still unchanged, etc. With the small masses provided, it is possible to vary $(M_1 - M_2)$ in 2 g steps from 0 to 70 g.

A string, whose mass per unit length is approximately the as that of the wire, hangs from the two masses. It serves to keep the mass of the string plus wire on each side approximately constant as the system moves, therefore it keeps the accelerating force constant.

PRECAUTIONS

In order to obtain satisfactory results in this experiment and in order to prevent damage to the apparatus, it is necessary to observe the following precautions: Release the brake only when the difference in mass on the two sides is less than 70 g. Preparatory to taking a run, raise the right hand mass until it just touches the bumper. Make sure that it does not raise the movable plate. Always release the brake when moving the masses. Keep your feet away from the descending mass.

Before releasing the brake, make sure that the left hand mass is not swinging.

Always stand clear of the suspended masses. The wire may break.

PROCEDURE

Start with a total load of 3500 g and all of the small masses on the left side. Move the left mass (M_2) to its lowest position, (see Fig. 1) Measure the displacement s, which is the distance from the top of the left mass to the bumper.

Transfer 10 g from the left to the right side (i.e. from M_2 to M_1, remember: if 10 g are transferred, then $M_1 - M_2$ will be 20 g). Make two determinations of the time of rise of the left hand mass through the measured distance. If the two time determinations differ by more than 5%, repeat the measurement until you obtain agreement within 5%. Compute the average acceleration using the average of the values of the time. It will be well to practice the timing before recording any results.

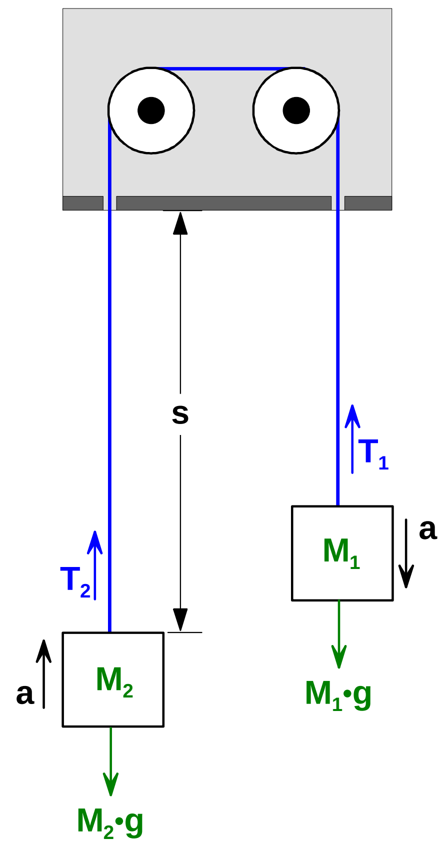


Figure 1: Atwood's machine

Increase the mass difference ($M_1 - M_2$) by about 10 g noting the time required in each case and compute the corresponding accelerations. At least six different mass differences should be used. Setup the data table in the following way, do not forget to note $M_1 + M_2$:

$M_1 - M_2$	time of rise [s]			displacement	acceleration
[g]	first	second	average	s [m]	$a = 2s/t^2$ [m/s^2]

ANALYSIS

Applying Newton's second law to the descending mass (see Fig. 1) we have,

$$M_1\, g - T_1 = M_1\, a \tag{1}$$

and to the ascending mass,

$$T_2 - M_2\, g = M_2\, a \tag{2}$$

where T_1 is the tension in the wire above the descending mass, T_2 the tension in the wire above the ascending mass, and g the acceleration due to gravity. T_1 will be greater than T_2 because there is friction and also because the wheels over which the wire runs are not without some mass, that means, a torque is required to accelerate them.

Adding (1) and (2) and solving for the acceleration we get

$$a = \frac{g}{M_1 + M_2} (M_1 - M_2) - \frac{T_1 - T_2}{M_1 + M_2} \tag{3}$$

where $(M_1 + M_2)$ is constant and $(T_1 - T_2)$ may also be considered as a constant if we assume that the friction remains constant as long as the total mass of the system does not change. If we plot the acceleration a versus the mass differences $(M_1 - M_2)$, then equation (3) is represented by a straight line of slope $g/(M_1 + M_2)$ and intercept $(T_1 - T_2)/(M_1 + M_2)$.

Consult the introduction to this manual for instructions concerning the graphing of data. Plot mass differences on the x-axis and corresponding accelerations the y-axis. Plot the data obtained on graph paper and draw the regression line which best "fits" the points. From measurements of slope and intercept, calculate g and $(T_1 - T_2)$. Your report should show your data table, graph, the method used to determine the slope and your calculations.

Questions (to be answered in your report):

1. What is the advantage of transferring mass from one side to the other, instead of adding mass to one side?
2. How would your results be changed if you gave the system an initial velocity other than zero?
3. Solve for the tension in the wire above the descending mass for the case of the largest acceleration. What would be the tension if $a = g$?

Buoyancy and Boyle's Law

Part A: Buoyancy and Archimedes' Principle

APPARATUS

1. Electronic balance with stand
2. Beaker
3. Metal object
4. Wooden block
5. Thread
6. Blue liquid

INTRODUCTION

The hydrostatic pressure P at a distance h below the surface of a fluid is given by

$$P = P_0 + \rho g h$$

where P_0 is the pressure at the surface of the fluid and ρ is the density of the fluid.

The hydrostatic pressure exerts a normal force on all surfaces in contact with the fluid. As a result there is a net upward force, called the Buoyant Force F_B, whose magnitude is equal to the weight of the fluid displaced, a relationship known as Archimedes' Principle.

$$F_B = \rho g V$$

where V is the volume of the object below the surface of the fluid. In this experiment, you will weigh objects in air and then measure the effect of submerging them in a fluid. A clearly labeled Free Body Diagram should be used to determine the forces on the submerged objects in order to relate your measurements to the density of the objects. If the fluid is water, assume the standard value for ρ of 1000 kg/m^3.

The electronic balance is turned on by pressing the button at the right. Pressing the button on the left quickly will change the units displayed. We will work with the gram scale. Note that this is the mass-equivalent of the force being measured, you do not have to actually multiply by the numerical value of g, leave it as a symbol and it will eventually cancel out.

PROCEDURE

Determine the density of a solid more dense than water. Weigh the metal object and then suspend it from the hook on the underside of the balance so that it is submerged in the beaker of water. This second weight, called the "apparent weight" differs from the first due to the buoyant force. Draw the corresponding Free Body Diagram and use it to determine the forces involved, and to solve for the density of the submerged object. Calculate the buoyant force and the density from your measurements. Use the table of densities on page 26 to estimate the composition of the metal. Does it appear reasonable from the appearance of the material? Explain.

An **alternate procedure** is to place the beaker on top of the scale and measure the change when the object is just submerged while being supported by the thread. Dry the metal object and weigh the beaker before (W_0) and after (W_1) the object is submerged. Do not let the submerged object touch the bottom of the beaker.

What force in the Free Body Diagram does ($W_1 - W_0$) represent? How was this force communicated to the bottom of the beaker? (Hint: what happened to the level of water in the beaker when the object was submerged?)

Determine the density of an object less dense than water. Weigh the wood block in air. Attach the metal object to it so as to act as a "sinker". Use either method to determine the density of the wood block. Explain the procedure that you chose, including appropriate Free Body Diagrams.

Use the table of densities on page 26 to make a guess as to the type of wood provided.

Determine the density of a liquid other than water. You now have objects whose densities are known. One of them can be used as a test object to determine the density of the unknown liquid. Be sure that the object you use is as dry as possible. Use one of the earlier procedures to determine the buoyant force on the object, and calculate the density of the liquid.

Use the table of densities to make a guess as to the composition of the unknown liquid.

Question (to be answered in your report):

How large a mass would have to be placed on top of the wooden block when floating in the water so that the block would be completely submerged, i.e. its top would be level with the surface of the water?

Part B: Boyle's Law

APPARATUS

1. Sealed hypodermic syringe
2. Set of hooked weights
3. Loop of string

INTRODUCTION

Boyle's law states that for a fixed mass of gas at a constant temperature, the product of the absolute pressure p and volume V is a constant:

$$p\,V = k \tag{1}$$

With a simple apparatus we can hang masses on the syringe plunger, thereby increasing the pressure on the gas inside the syringe to a value above atmospheric pressure. The volume can be read from the scale on the side of the syringe. The scale is in units of cc which means cm^3. If the pressure added by the weight of the masses is p_{add} and the atmospheric pressure is p_{atm}, then the resulting total pressure is $p_{total} = p_{atm} + p_{add}$.

PROCEDURE

1. Record the current atmospheric pressure and temperature as indicated by your instructor. (If the current temperature is not available, assume 68°F = 20°C.) Atmospheric pressure may be given in mbar or bar, where 1 bar = 10^5 Pa. Convert to Pascals.

2a. Check that the syringe is held firmly in the clamp and is vertical. Examine the scale and record the volume V_0, indicated by the bottom edge of the plunger.

2b. Record the sensitivity of the scale, that is, the smallest quantity that can be read or estimated on it. We will use this value as the uncertainty of our volume measurements.

2c. How many digits of V_0 are actually significant? (See the discussion on significant figures in the introduction of the lab manual.)

3. We use a string to hang masses on the plunger. The weight of this mass acting on the area of the plunger will increase the pressure of the trapped air and therefore change the volume. We can simplify the calculation of added pressure for each value of mass by considering the pressure p_1, at a load of 1 kg . There are four calculations:

(i) the weight of 1 kg, W_1,
(ii) the area of the face of the plunger A, (radius of the plunger = 0.715 cm),
(iii) the pressure added by the weight, $p_1 = W_1/A$, and
(iv) conversion of the units to the standard unit of pressure, the Pascal. (1 Pa = 1 N/m^2)

Check : p_1 should be about 3/4 of an atmosphere (1 atmosphere = 1.013×10^5 Pa).
Finally, trim p_1 to the number of significant figures found in 2c. (One extra digit may be kept as a guard digit to avoid round-off problems.)

4. Use the headings below to prepare a table for your data. Note the second line of the heading that contains the multiples and units to be used.

Mass M [kg]	Volume V [10^{-6} m^3]	p_{add} [10^5 Pa]	p_{total} [10^5 Pa]	$1/p_{total}$ [10^{-5} Pa^{-1}]
0	V_0	0	p_{atm}	
...	...			

Your first entry will be for Mass = 0, and Volume = V_0 as found in 2a. Note that the units have to be converted to m^3 (1 cm = 10^{-2} m $\longrightarrow$ 1 cm^3 = 10^{-6} m^3). p_{add} will be zero, and therefore p_{total} is just equal to the atmospheric pressure.

5. Use the string to hang weights on the plunger. Use values of 500, 700, 1000, 1200 and 1500 g. Wait at least a minute after each weight is added, so that the gas can come back to room temperature. Increase the waiting time at the larger loads, so that the gas can return to room temperature after being compressed. Use the time to complete some of the calculations outlined below. Record the volume and complete the line in the table. Remember that $p_{add} = [M/(1 \text{ kg})] \times p_1$, where p_1 is the additional pressure due to a 1-kilogram weight. Trim p_{total} of any digits that are not significant.

ANALYSIS

1. We will use Boyle's law in the form:

$$V = k\,(1/p) \tag{2}$$

Calculate all the reciprocals and put them into the last column of the table.

2a. Plot the graph of V vs. $1/p_{total}$. The origin should be included, although it is not a data point. Be sure that your scales allow the graph to occupy most of the page. (We are following the usual practice of plotting the dependant variable on the y-axis.)

2b. Draw the single straight line that best represents the data. Use a transparent straight edge (like a plastic ruler) to help fit the line. The line should be drawn completely across the graph.

2c. Choose two points on the line (not data points) that are widely separated to use in calculating the slope. Note that the slope will have units. Record this value as k_{slope}.

3. The graph of equation 2 would go through the origin. With experimental data, the straight line usually comes close to, but misses the origin. Determine the positive intercept with either axis. Assume that the uncertainties in the value of these intercepts are 0.2 cm^3 and $0.04 \times 10^{-5}\text{Pa}^{-1}$, respectively.

We can see whether this intercept is consistent with 0 by calculating the uncertainty ratio, your intercept value divided by the appropriate uncertainty value. A small ratio (less than 2) indicates good agreement. Large values (greater than 5) means disagreement. Intermediate values can be described as 'fair' or 'poor' agreement and usually require further study.

4. The constant k can also be determined from the Ideal Gas Law, $p\,V = n\,R\,T$, where n is the number of moles of gas $(\rho V_1/MW)$, R is the gas constant (8.31 J/mol·K) and T is the absolute temperature in Kelvin. V_1 is the volume measured at a load of 1 kg and ρ is the corresponding density. For air, 80% $^{14}N_2$ and 20% $^{16}O_2$, the molecular weight MW $= 29 \times 10^{-3}$ kg/mol, and $\rho = 2.13$ kg/m^3 at the 1-kg load and room temperature. Calculate $n\,R\,T$ from the data given, and compare with k_{slope}, assuming an uncertainty in k_{slope} of 0.2×10^5 Pa·cm^3.

Questions (to be answered in your report):

1. (a) What curve would equation 1 describe in a graph of p vs. V?
   (b) How could we graph our data so as to obtain a straight line with slope k ?

2. How does your value of k_{slope} agree with $n\,RT$? The uncertainty ratio here is

$$\frac{|k_{slope} - n\,RT|}{\text{uncertainty in } k_{slope}}$$

3. If the uncertainty in the slope is ΔV (from procedure 2b.) divided by the range of your $(1/p)$ values, what is your uncertainty in k_{slope} ?

Density Table

Metal	ρ **[g/cm³]**
Aluminum	2.7
Brass (ordinary yellow)	8.40
Bronze - phosphor	8.80
Copper	8.90
Gold	19.3
Iron - wrought	7.85
Iron - gray cast	7.1
Lead	11.3
Steel	7.8
Tungsten	19.3
Zinc - wrought	7.2
Balsa wood (oven dry)	0.11 ... 0.14
Ebony	1.11 ... 1.33
Oak	0.6 ... 0.9
Pine - white (oven dry)	0.35 ... 0.50

Liquid	ρ **[g/cm³]**
Alcohol, Methyl	0.80
Carbon Tetrachloride	1.60
Gasoline	0.68
Mercury (20°C)	13.55
Water (0°C)	0.999
Water (4°C)	1.000
Water (15°C)	0.997
Water (100°C)	0.958

Stone	ρ **[g/cm³]**
Granite	2.7
Limestone	2.7
Marble	2.6 ... 2.8
Mica schist	2.6
Sandstone	2.1 ... 2.3

Centripetal Force

APPARATUS

1. Centripetal force apparatus
2. 30 cm ruler
3. Set of slotted weights
4. Stop clock
5. Equal-arm balance with standard weights
6. Electric stop-clock

INTRODUCTION

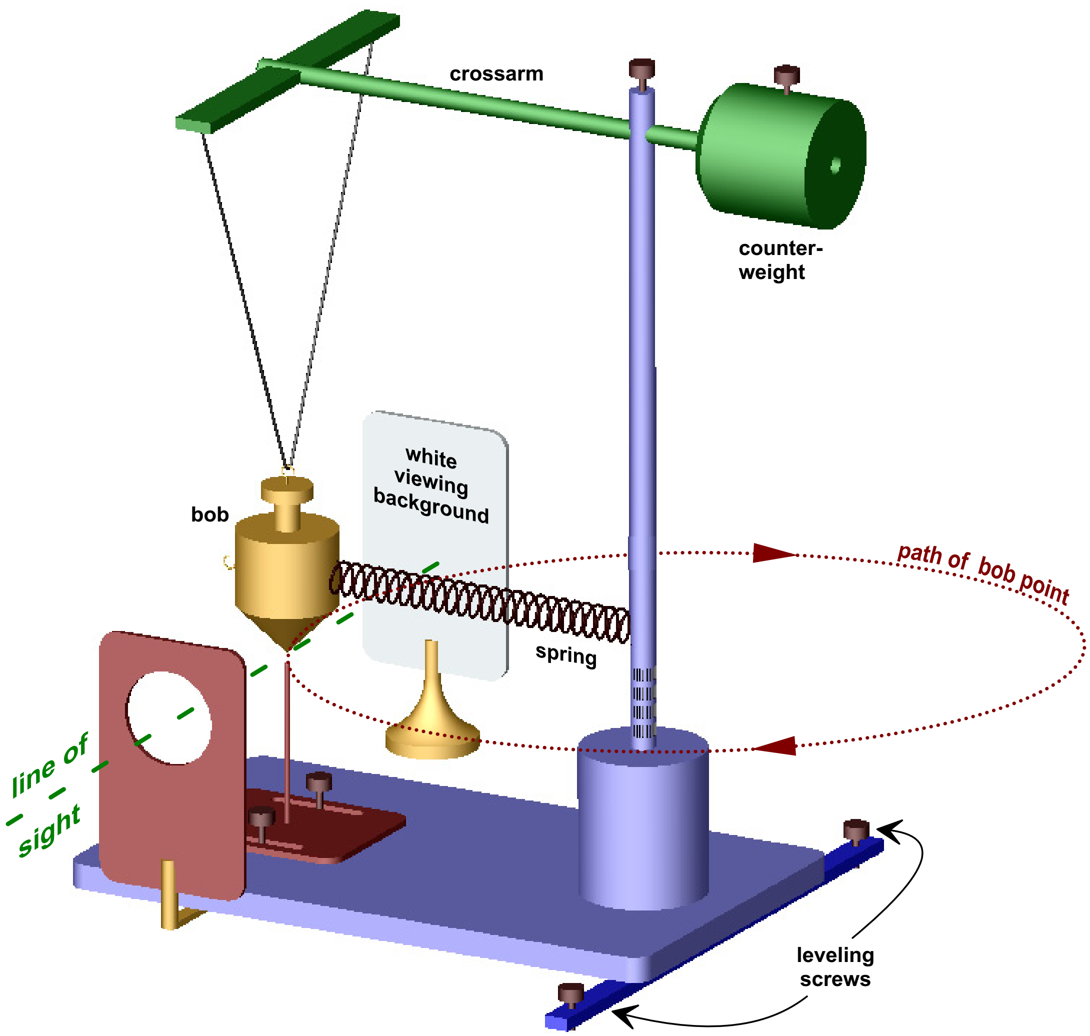


Figure 1: Centripetal force apparatus

A mass m moving with constant speed v in a circular path of radius r must have acting on it a centripetal force F, where the relationship between these quantities is

$$F = \frac{mv^2}{r}$$

Since v for this particle is given by $2\pi r/T$ or $2\pi rf$, where T is the period (seconds per revolution or s) and f is the number of revolutions per second or s^{-1}, then

$$F = \frac{m\,(2\pi rf)^2}{r} = 4\pi^2 mf^2 r \tag{1}$$

In this experiment the mass that we examine as it moves in a horizontal circle is the bob in the apparatus shown in Fig. 1. As indicated in Fig. 1, the shaft, cross arm, counterweight, bob and spring are all rotated as a unit. The shaft is rotated manually by twirling it repeatedly between your fingers at its lower end, where it is knurled. With a little practice it is possible to maintain the distance r essentially constant, as evidenced for each revolution by the point of the bob passing directly over the indicator rod, The centripetal force is provided by the spring.

The indicator rod is positioned in the following manner: with the bob at rest with the spring removed, and with the crossarm in the appropriate direction, the indicator rod is positioned and clamped by means of thumbscrews such that the point of the bob is directly above it, leaving a gap of between 2 and 3 mm.

The force exerted by the (stretched) spring on the bob when the bob is in its proper orbit is determined by a static test, as indicated in Fig. 2.

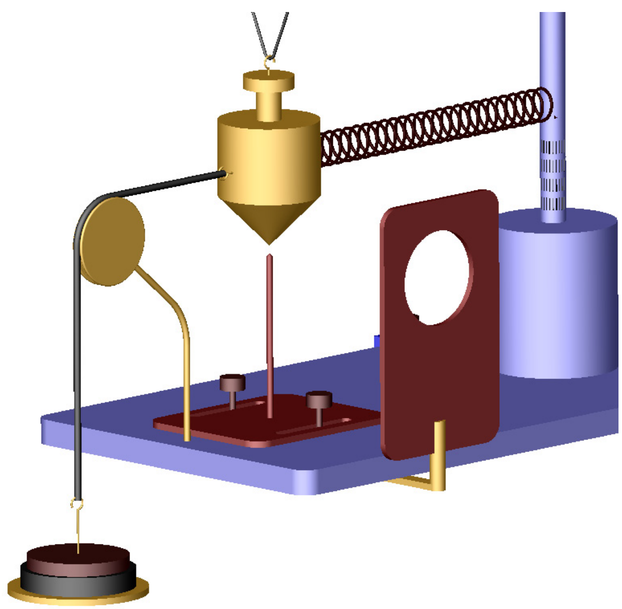


Figure 2: Static test

The mass m in Eq. 1 is the mass of the bob. A 100 g mass (slotted) may be clamped atop the bob to increase its mass.

The entire apparatus should be leveled so that the shaft is vertical. Notice that viewing should be done through the hole in the guard, against a white background.

PROCEDURE

Make any necessary adjustments of the three leveling screws so that the shaft is vertical.

The detailed procedure for checking Eq. 1 experimentally will be left to the student. At least two values of r should be used, with two values of m for each r. A method for measuring r should be thought out, the diameter of the shaft is 1.27 cm. The value of f should be determined by timing 50 revolutions of the bob and then repeating the timing for an additional 50 revolutions. If the times for 50 revolutions disagree by more than one-half second either a blunder in counting revolutions has been made, or the point of the bob has not been maintained consistently in its proper circular path. In either case, the measurement should be repeated until a consistent set of values is obtained. It is suggested that you read the next section, on results and questions, before doing the experiment.

RESULTS AND QUESTIONS

1. Exactly from where to where is r measured? Describe how you measured r.
2. Tabulate your experimental results.
3. Tabulate your calculated results for f, F from static tests, and F from Eq. 1 and the relative difference between the F's (in %), using the static F as standard.
4. Describe how to test whether the shaft is vertical without the use of a level. Why should it be exactly vertical?
5. What are the functions of the guard, the white background, and the counterweight on the crossarm?
6. Discuss your results.

Diffraction Grating and Interference

APPARATUS

1. Spectrometer
2. Diffraction grating
3. Mercury arc lamp
4. Board for mounting glass plates
5. Two plane parallel plates of glass
6. Aluminum stand equipped with a lens, a mirror inclined at 45°, and an index.
7. Sodium lamp
8. Metric ruler (30 cm)

On the instructor's desk the student will find:

9. A hydrogen Geissler tube
10. Tissue paper for cleaning the glass plates
11. A thin strip of paper
12. A small strip of steel

INTRODUCTION

Part I: The Grating Spectrometer

A diffraction grating consists of a large number of fine, evenly spaced parallel slits. There are two types: transmission and reflection gratings. There are two kinds of transmission gratings; one kind has lines ruled on glass, the unruled portions acting as slits, the other kind is a replica of the reflection type. It consists of a piece of gelatin mounted between two pieces of glass, the thinner portions of the gelatin acting as the slits. The reflection grating is formed by ruling lines on a polished metal surface; the unruled portions produce by reflection the same result as is secured by transmission with the other type.

The purpose of this exercise is to measure the wavelengths of several spectral lines. The transmission grating, to be used in conjunction with a spectrometer, is a replica. It has from 5,000 to 6,000 lines per cm; the exact number is usually found on the grating.

Let the broken line, MN, in Fig. 1 represent a magnified portion of a diffraction grating. Waves start out from all of the slits in phase, so that the phase difference at F between waves from A and C corresponds to the path difference AB. This same difference at F will be present between waves from each two successive slits in the grating. Hence, if AB is equal to λ, or 2λ, or 3λ, etc. where λ is the wavelength of the light, waves from all the slits will constructively interfere at F and we shall get a bright image. The images at F when AB = λ, 2λ, 3λ, etc. are called the first order spectrum, second order spectrum, third order spectrum, etc., respectively. It is seen from Fig. 1 that, if θ is

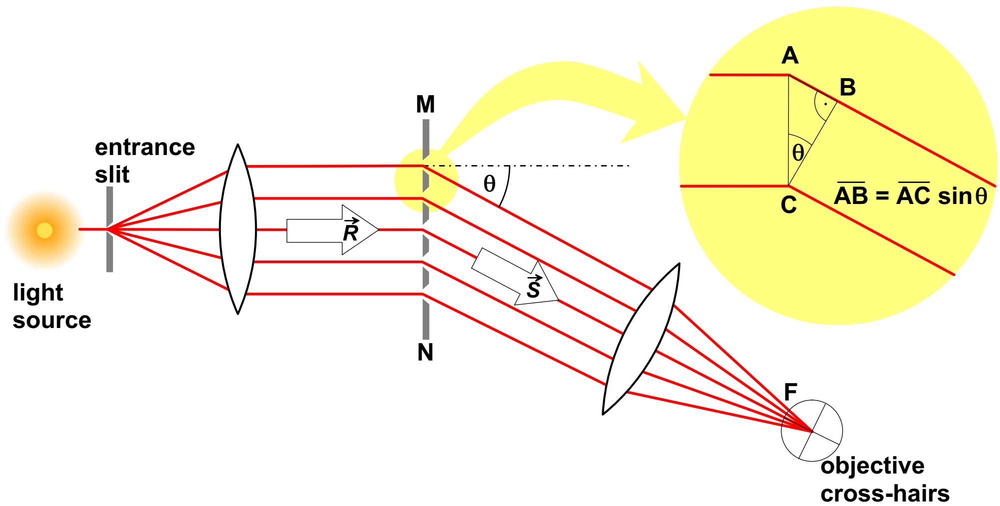


Figure 1: Schematic layout of the spectrometer.

the angle of diffraction, or the angle that the rays forming the spectrum make with the original direction of the light $\vec{R}$, d the grating spacing, or distance between the centers of adjacent slits, λ the wavelength of the light, and n the order of the spectrum, then

$$\frac{n\,\lambda}{d} = sin\,\theta \qquad \text{or} \qquad n\,\lambda = d\,sin\,\theta \tag{1}$$

is the condition that the waves from the various slits constructively interfere wich each other.

If the light is not monochromatic, there will be as many images of the slit in each order as there are different wavelengths in the light from the source, the diffracting angle for each wavelength (color) being determined by equation (1).

Part II: Interference at a Wedge

A method for measuring the wavelength of light is to allow monochromatic light to be reflected from the two surfaces of a very thin film of varying thickness, thus producing an interference pattern. Wherever the two waves reflected from the surfaces of the film meet in phase, a bright spot will be produced, and where they meet differing in phase by one-half a wavelength, a dark spot will appear. If the film varies regularly in thickness, the interference pattern will consist of a series of parallel bright and dark line, called interference fringes.

In this experiment, the thin film consists of the air space between two approximately plane parallel plates of glass, separated at one end by a thin strip of paper of thickness T, as shown in Fig. 2. When the ray A reaches the point x at the top of the air film (inset of Fig. 2), it is partially reflected, forming ray B. Part of ray A will also be reflected from the bottom of the air film at point y forming the ray C. if the phase difference between the rays B and C corresponds to an integral number of wavelengths, say 14, they will be in phase, which will result in a bright fringe

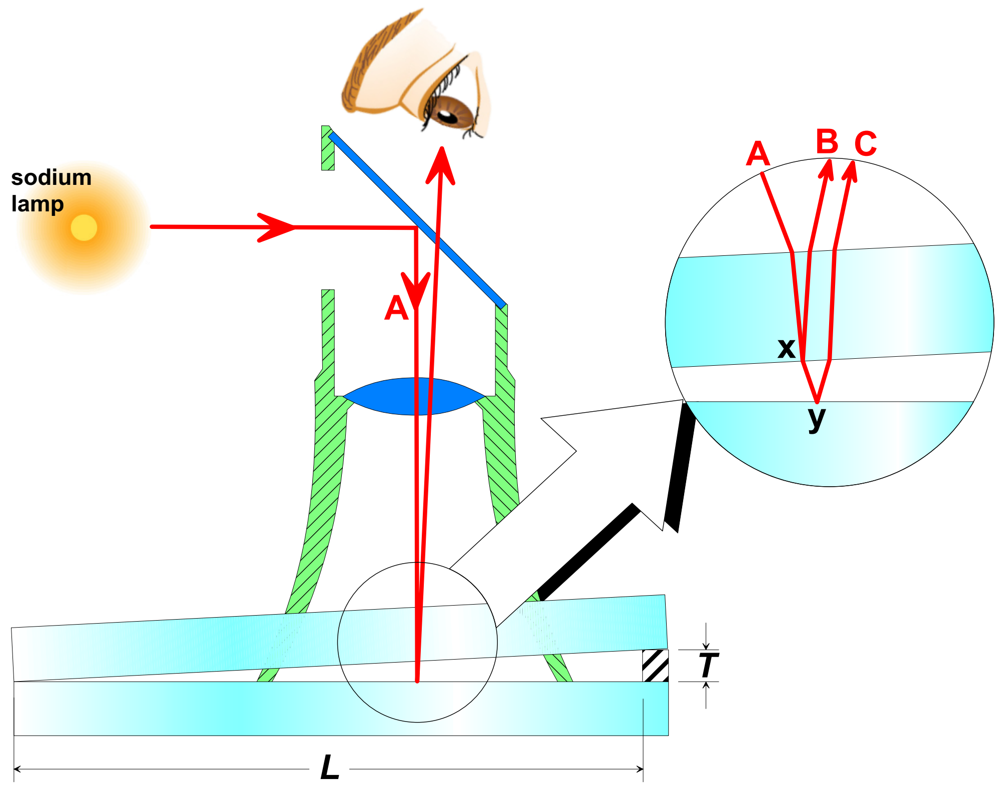


Figure 2: Setup for observation of interference fringes at two glass plates.

at this point of the air film. If we move toward the thicker end of the film, the next light fringe encountered, must correspond to the next integral number of wavelengths of phase difference; that is 15. To produce this one-wavelength increase in phase difference, the thickness of the film must have increased by a half-wavelength. (Why?) Therefore, if traveling from one fringe to the next corresponds to an increase in film thickness of one-half wavelength, traveling the entire length of the film, L must correspond to an increase in film thickness of N half-wavelengths, where N is the total number of fringes in the length L. Because the difference in thickness between the two ends of the film is known to be T, we have the equation

$$N\,\frac{\lambda}{2} = T \tag{2}$$

By measuring N and T, the wavelength of the light might be computed. However, since it is convenient to measure the number of fringes per centimeter, η, one may use the formula in the form

$$\eta\, L\,\frac{\lambda}{2} = T \tag{3}$$

Since the above reasoning will apply to the dark fringes as well as to the light, either set may be counted - whichever is most convenient.

PROCEDURE

Part I: The Grating Spectrometer

The appropriate device for producing the required parallel rays, holding the grating, focusing the diffracted light, and permitting the determination of angles from a graduated circular scaled is called a spectrometer (see Fig. 3). **PLEASE TREAT IT CAREFULLY - it is expensive to repair.**

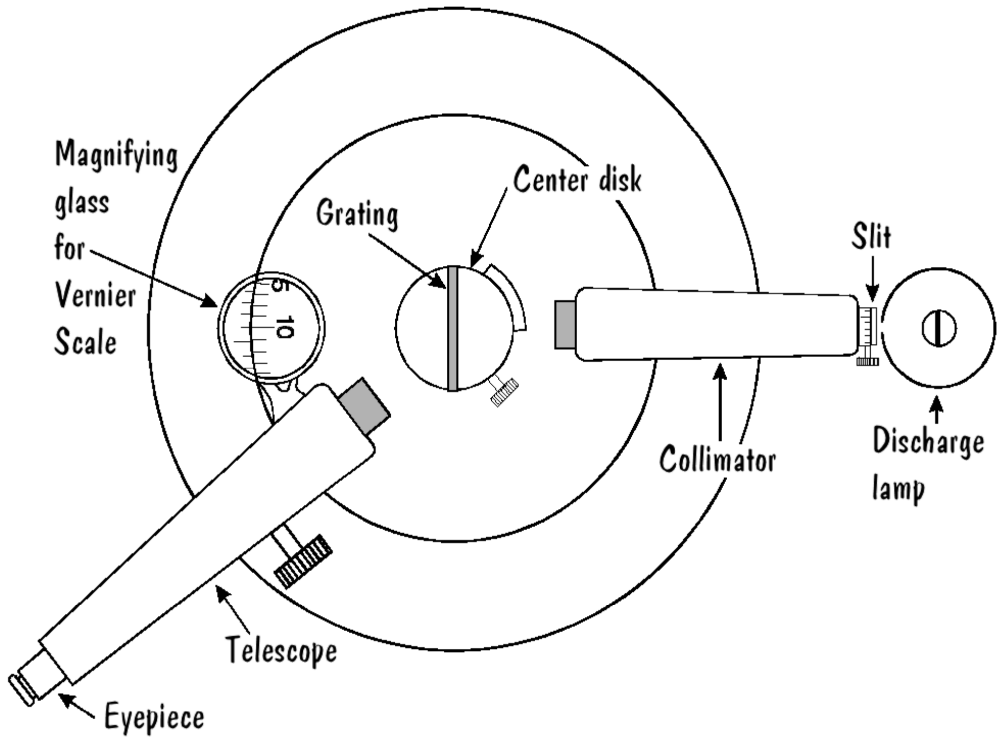


Figure 3: Parts of the grating spectrometer.

In order to use the instrument you will need only to vary the width of the slit (controlled by the knurled ring surrounding it) and to rotate the telescope. Your instructor will show you how the telescope can be moved quickly and then how the slow-motion screw can be engaged to permit very slow precise movement. Do not turn the leveling screws! The grating should be adjusted so that its surface is perpendicular to the axis of the collimator and then clamped in this position.

The magnifying glasses aid in reading the verniers which enable the setting of the telescope to be measured to the nearest minute of angle. See the notes on Angle Scale Verniers in the Introduction on page 11.

Place the Mercury lamp directly in front of the slit of the collimator. Upon looking with the unaided eye through the grating and collimator you will see the slit brightly illuminated. The slit should be made quite narrow. Now look through the telescope. First focus upon the cross-hairs by moving the tube holding the eyepiece lens. Next focus upon the slit by moving the tube that holds the slit without disturbing the focus of the cross hairs. Both must be in sharp focus. Set the cross-hairs on the image by use of the slow-motion screw, and note the reading of one of the verniers. This setting of the telescope corresponds to the direction $\vec{R}$ in Fig. 1.

Turn the telescope either to the right or to the left, make a similar setting on a line of the spectrum and read the same vernier. This position of the telescope corresponds to the direction $\vec{S}$ in Fig. 1. θ, the angle through which the telescope was turned, which is the difference between the two readings of the vernier, is the angle of diffraction. (**Attention:** If the vernier has passed through the 360° or 0° mark while turning the telescope, allowance for this will have to be made in the subtraction.) The wavelength λ of the line observed may now be calculated by use of equation (1).

In this manner determine the wavelengths of at least four lines in both first and second orders on both sides of the central image. Tabulate your values of λ and compare them with those found in the table at the end of this experiment (page 35).

Part II: Interference at a Wedge

Be sure that the glass plates are clean. Handle them carefully and avoid getting finger marks on the surfaces which are to be placed together. Your instructor will inform you of the thickness of the paper. Mount the glass plates on the board and place the strip of paper between the ends of the glass plates. Place the frosted surfaces down with the ruled lines on the inside. Measure the length L. Now place the aluminum stand containing the lens and the mirror over the center of the wedge-shaped air film, and place the sodium lamp at a convenient distance opposite the hole in the side of the aluminum stand. The interference pattern will consist of a series of dark lines across the image of the flame. These parallel lines should be perpendicular to the length of the air film. Make two counts of the number of dark lines in two centimeters of length. Now calculate the wavelength of the yellow light. Express your results in nm (1 nm = 10^{-9}m).

Part III: Measurement of the Thickness of a Steel Strip

Replace the paper strip by a strip of steel. Measure its thickness with the aid of the sodium lamp assuming your value of the wavelength of the light to be correct. Question: In deriving Equation 2, an expression of the type ”phase difference corresponding to 14 wavelengths” was used instead of ”path difference of 14 wavelenghts”. Why do these two expressions differ in meaning for this experiment? (Refer to the text on phase change in reflection.)

Part IV: Hydrogen Lines

If time permits, measure the wavelengths of the three bright lines of the hydrogen spectrum, using the spectrometer.

Wavelength of Spectral Lines

Mercury (Mercury Lamp)

Bright Violet	404.7 nm
Violet	407.8 nm
Blue	435.8 nm
Dull Green	491.6 nm
Bright Green	546.1 nm
Yellow	577.0 nm
Yellow	579.1 nm

Hydrogen

H_γ, blue	434.0 nm
H_β, dull green	486.1 nm
H_α, red	656.3 nm

Potassium (KCl in flame)

Red	766.8 nm
Red	770.2 nm

Sodium

Orange	588.9 nm
Orange	589.5 nm

Elasticity and Simple Harmonic Motion

APPARATUS

1. Balance and set of known masses
2. Two cylindrical springs
3. A set of five masses: 100, 200, 200, 500 and 1000 g (Hook type)
4. Upright meter stick with a movable index attached
5. Stop clock

PROCEDURE

<u>Part I: Elasticity of a body</u>

Since no real body is perfectly rigid the application of a force will distort it. A perfectly elastic body will return to its original form after the removal of the distorting force.

The elasticity of the cylindrical spring may be tested by comparing the position of some point on the spring before each of several loads is added with the position of the point after each load is removed.

Using the vertical meter stick observe the position of some point at the lower end of the spring. Add a load of 400 g and again note the position of the point on the spring. Increase the load by 200 g and repeat the observation. Remove the loads, one at a time, compare the position of the reference point after each load is removed with its corresponding original position.

<u>Part II: Dependence of the distortion on the distorting force</u>

For many bodies the force, within limits, produces a distortion which is proportional to the force. The limits within which this proportionality exists depends upon the material of which the body is made and upon the form of the body.

The body to be studied is a closely wound cylindrical spring. A force large enough to produce a permanent elongation is easily conceivable. Adjacent turns of this spring may press so tightly together that some pull is required to relieve this compressional tendency before the spring can begin to be stretched. There is possible, then, an upper and a lower limit to the force which can be applied to the spring, between which the distortion is proportional to the force.

1. Observe the position of some reference point on the lower end of the spring as in Part I. This is the zero reading.

2. Apply a load of 100 g and note the new position of the reference point.

3. Repeat, adding 100 g each time, until the total load supported is 1000 g.

4. Determine the elongation produced by each load by subtracting the zero reading from each subsequent reading.
5. Show the dependence of the elongation upon the applied force by plotting the elongation as y-axis and the corresponding total force as x-axis.
6. Determine from the curve the range of forces used in which the elongation is proportional to the force.
7. Remove the load 100 g at a time, taking the scale reading in each case. Are these readings the same, for each load, as those found above?

Part III: Force constant of the spring

The force constant of the spring is the force ΔF required to produce an elongation Δl in the spring. In symbols, this may be expressed as $k = \Delta F/\Delta l$ in units of N/m. This is a constant only for the range of forces within which the proportionality of Part II exists.

Determine an average value of the force constant of the spring from the curve plotted in Part II.

Part IV: Dependence of the period in simple harmonic motion on the vibrating mass

Consider a body, for which the distortion is proportional to the force producing it, held away from its normal position. There is now a restoring force in the body, which is proportional to the distortion. If the force applied to the body is removed, this restoring force returns the body to its normal position. However, its inertia carries it through that point producing a distortion or displacement on the other side. Now the action of the restoring force first brings the body to rest in a distorted position. The action is repeated and this simple harmonic motion continues until it is stopped by friction.

As an example, consider as the body the spring with a load of 500 g suspended from it. Reference to the data of Part II will show that now, the spring is in a condition where any additional force will produce a proportional displacement. If the load is pulled down some distance x and released, a restoring force $-k\,x$ acts on the body. As the body moves back to its equilibrium position, this restoring force diminishes. The minus sign indicates that the restoring force is opposite to the distortion. Since $-kx$ is an unbalanced force, it produces an acceleration a. From Newton's Law, $F = M\,a$, we get $-k\,x = M\,a$, where M is the mass of the system and the negative sign shows that x and a are oppositely directed. This yields

$$-\frac{x}{a} = \frac{M}{k} \tag{1}$$

The period T in simple harmonic motion is given by

$$T = 2\pi\sqrt{\frac{M}{k}} \tag{2}$$

Here, M is the mass of the vibrating system consisting of the mass suspended from the spring (500 g in the example) plus a part of the mass of the spring. It can be shown that one third of the total mass of the spring is the part effective in determining the total M.

1. Determine the period of the simple harmonic motion occurring when the load on the spring is 500 g. Determine the average time required for at least fifty vibrations.
2. Repeat with loads of 600, 700 and 800 g.
3. Measure the mass of the spring.
4. Using equation (2), calculate the period to be expected in each case. Compare them with the experimental values of the periods. Obtain both, the difference and the percent difference.
5. What percentage error would be introduced in the calculated values of T for the 500 g load and the 800 g load, respectively, if the mass of the spring were neglected?
6. Plot two curves: $T(M)$ and $T^2(M)$ (the period and the square of the period of vibration vs. the mass supported by the spring)

Part V: Dependence of the period on the amplitude

The maximum value of the displacement in simple harmonic motion is the amplitude.

Using a load of not over 600 g, try varying the initial amplitude of the vibration and note the effect on the period. Does the period depend upon the amplitude?

Electric Potential, Electric Field

APPARATUS

1. Plotting Board with Teledeltos Paper
2. Electronic Voltmeter
3. D.C. Power Cord
4. Ruler

INTRODUCTION

When an electric potential difference is established between two conductors there will be an electric field between them. There will also be an electric potential difference $V(x, y, z)$ between any point in space and one of the conductors. In general, it is difficult to calculate V. However, in situations having a high degree of symmetry, Gauss's Law allows a simple calculation of the electric field, from which V can be easily calculated by integration.

This experiment mimics the case of cylindrical symmetry by using a sheet of high resistance conducting paper on which concentric circular conductors are placed. A very small current will flow through the paper guided by the electric field at each point. An electronic voltmeter is used to measure the electric potential difference between points on the paper and one of the electrodes. The voltmeter itself has such a high resistance that it does not disturb the field. Once the potential has been determined at different positions, the electric field can be determined by finding the gradient of the potential.

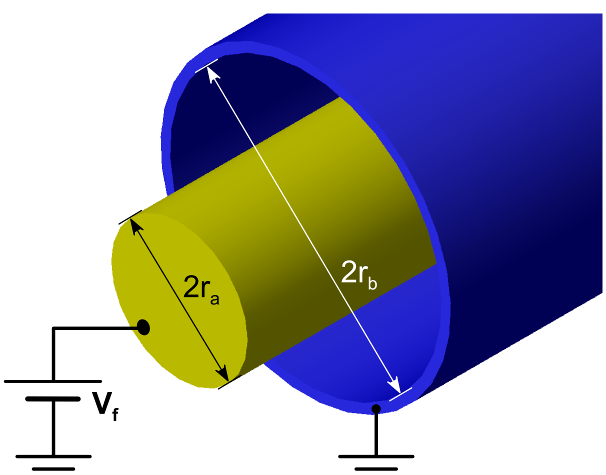


Figure 1: Coaxial arrangement of two conductors.

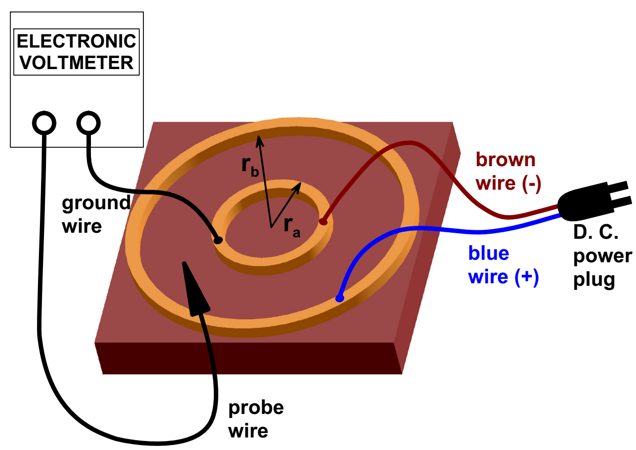


Figure 2: Wiring diagram.

EXPERIMENTAL ARRANGEMENT

The arrangement of concentric cylindrical conductors which we are considering is shown in Fig. 1. Our laboratory arrangement is illustrated in Fig. 2. The electrodes rest on a sheet of uniform conducting paper (trade name TELEDELTOS) so that it is equivalent to a plane section through Fig. 1, perpendicular to the axis of symmetry. Thus, when the terminals of a DC supply are connected to the electrodes, as shown in Fig. 2, the variation in potential between the electrodes will be the same as between the two cylinders of Fig. 1. Potential differences will be measured between points on the paper and the inner electrode.

MEASUREMENT PROCEDURE

A. Determine the radii

r_a is the outer radius of the inner ring. r_b is the inner radius of the outer ring. Measure the diameters to the nearest mm and divide by 2.

B. Wiring

Be sure that the DC power plug is NOT connected to the outlet. It is to be plugged in only after your wiring has been approved by your instructor.

Examine the wiring under the plotting board to see which binding post is connected to the inner electrode. Connect the brown wire (ground) of the DC power cord to this binding post. Connect the blue wire (+) to the outer electrode via the other binding post. Check that the black lead from the voltmeter is plugged into COMMON and that the probe end has an alligator clip on it. Clip it to the screw projecting from the inner electrode. The red lead should he plugged into V-Q-A. This lead will be used to probe the field. HAVE YOUR INSTRUCTOR CHECK YOUR WIRING. If it is approved, you may plug the DC power cord into the special outlet.

C. Set up the Voltmeter

Turn the voltmeter dial to 10 Volts on the DC side. Set the polarity switch to +. Touch the probe to the inner ring. If the meter does NOT read zero, call your instructor.

D. Read the potential difference at various values of r

Positions may be measured from the edge of the inner electrode. The radius may then be calculated by adding the radius of the inner electrode as measured in A. Set up a data table with columns for: distance, radius, V_1, V_2, V_3, and V_{avg}. V_1, V_2, and V_3, are to be measured along three different radii and averaged in the last column.

Gently touch the voltmeter probe to the paper at a point about 5 mm from the edge of the inner electrode. **Do not press hard enough to damage the paper.** Record this data point in your table. Continue along the same radial direction, taking readings every 5 mm.

Repeat for two other radii at about equal angles.

ANALYSIS

A. Linear Plot

Plot the average potential difference against radial distance. Draw a smooth curve that approximates the data points. The theoretical relationship between V and r for the geometry of Fig. 1 is given by

$$V(r) - V(r_a) = constant \times ln\left(\frac{r}{r_a}\right) \tag{1}$$

where the constant is proportional to the potential difference between the electrodes. Given the dimensions of the apparatus and small irregularities in the paper, it may be difficult to see that the data follow equation (1).

B. Semi-Log Plot

If V is plotted against $log_e(r)$, a linear plot should be obtained. Semi-log graph paper has markings along one axis whose distance is proportional to the $log_{10}(x)$, where values of x between 1 and 10 appear on that axis. This means that you do **not** have to calculate logarithms. V is plotted along the linear axis. Plot your data for V vs. r.

Do the data confirm the form of equation (1)? Draw the best straight line that fits the data.

You may notice that the straight line does not intersect the lines for r_a and r_b at the appropriate values of V. This is due to oxidation and poor contact at the copper-paper interface.

C. Cylindrical symmetry

Choose one value of the radius, about 2 cm from the inner ring, and examine the potential difference at several angles different from the data taken earlier. Recognizing that small variations are possible, do your data indicate cylindrical symmetry? Explain your answer

D. Electric Field

The electric field E, at any point may he found from

$$E_r = -\frac{dV(r)}{dr} \tag{2}$$

Choose about six points on the linear plot of part IV.A and use the tangents to your curve at these points to determine E_r.

Applying equation (2) to $V(r)$ from equation (1) yields

$$E_r = constant \times \frac{1}{r} \tag{3}$$

Prepare a table of your values of E (in Volts per cm), r (in cm) and $\frac{1}{r}$. Plot E_r vs. $\frac{1}{r}$ on linear graph paper. Do your data fit a straight line as indicated by equation 3?

E. Other Regions

According to Gauss's Law applied to the situation of figure 1, there should be no electric field outside the outer ring or inside the inner ring. Explore the value of the electric potential in these two regions. (The values may not be zero because of the imperfections mentioned previously.) What do your values for the potential indicate about the electric field outside the outer ring? Inside the inner ring? Explain your reasoning. QUESTION: If your data for V(r) corresponded to the geometry of figure 1, would the charge on the inner conductor be positive or negative? Explain your reasoning.

Electrical Resonance
(R-L-C series circuit)

APPARATUS

1. R-L-C Circuit board
2. Signal generator
3. Oscilloscope Tektronix TDS1002 with two sets of leads (see "Introduction to the Oscilloscope" on page 12)

INTRODUCTION

When a sinusoidally varying force of constant amplitude is applied to a mechanical system the response often becomes very large at specific values of the frequency. The phase difference between the driving force and the response also varies, from close to 90° when far from resonance to 0 when resonance occurs.

Resonance occurs in electrical circuits as well, where it is used to select or "tune" to specific frequencies. We will study the characteristics of sinusoidal signals and the behavior of a series R-L-C circuit.

First we review the mathematical description of the behavior of the R-L-C circuit when connected to a sinusoidal signal. Since current is the same at all points in the series R-L-C circuit, we write:

$$I = I_0\, sin\, \omega t \quad \text{where} \quad \omega = 2\,\pi\, f$$

The voltages across each component are then:

$$V_R = I_0\, R\, sin\, \omega t \tag{1}$$

$$V_L = I_0\, \omega\, L\, sin(\omega t + \pi/2)$$

and

$$V_C = I_0 \left(\frac{1}{\omega C}\right)\, sin(\omega t - \pi/2)$$

The sum of these voltages must equal the supply voltage:

$$V_s = V_0\, sin(\omega t + \phi)$$

where

$$V_0 = I_0\, Z \quad \text{and} \quad Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \tag{2}$$

Z is called the impedance and is a minimum when

$$\omega L - \frac{1}{\omega C} = 0 \tag{3}$$

Under this condition, called resonance, the phase shift between the supply voltage and the current is also zero. This phase shift is given by the phase angle ϕ:

$$tan\,\phi = \frac{\omega L - \frac{1}{\omega C}}{R} \tag{4}$$

Equation 3 can be used to determine the **resonance frequency** f_0. Engineers use the half-power frequencies f_1 and f_2 (see Fig. 1) as a measure of the width of the resonance, these are the frequencies, where $I_0(f_1) = I_0(f_2) = I_0(f_0)/\sqrt{2}$
and consequently, $\phi = 45°$.

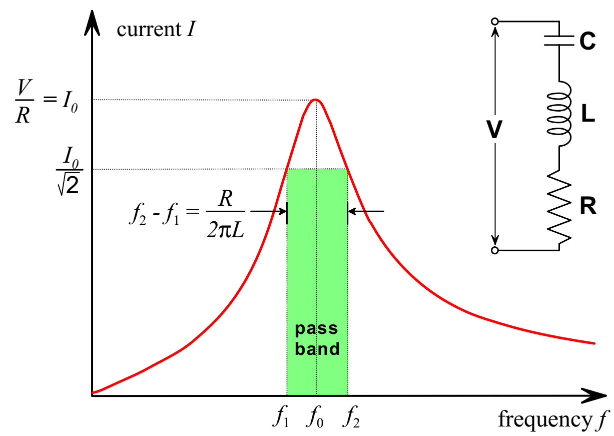


Figure 1: Resonance in the R-L-C series circuit.

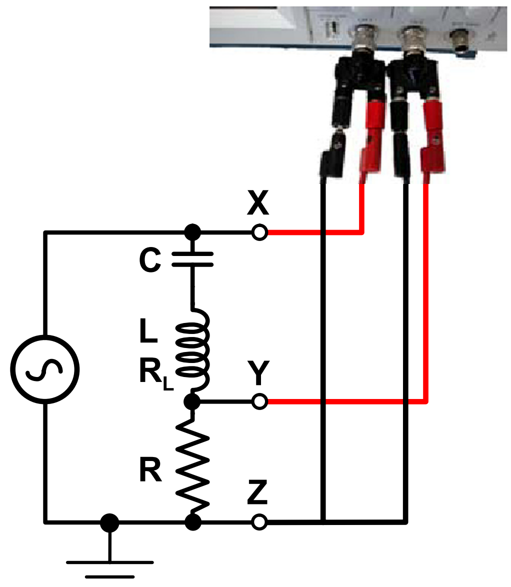


Figure 2: Wiring diagram.

PROCEDURE

Part 1: Setting up the circuit

1a. Examine the circuit board. Copy the data from the card on the bottom of the board including the circled board number. (If you need to come back at a later time, you will need to use the same board.)
NOTE: In this experiment there are two resistances, one (R) used to sense the current, and the resistance of the wire that forms the inductor(R_L). Equations 2 and 3 refer to the sum of the resistances, $(R + R_L)$ while we will apply equation 1 separately to the current sensing resistor R.

1b. Identify each component on the circuit board. Note the labels on the diagram.

1c. Review the notes on the oscilloscope. Two cables have been provided for the oscilloscope. Connect the cable with the plugs to CH1, and the plugs to points X and Z, being careful about ground connections (black plug to the black jack - point X). CH1 will display the AC voltage supplied to the circuit, V_0.

1d. Connect the cable with the clips to CH2, and the clips to the solder lugs on either side of the resistor (points X and Y), with the ground side (black wire) next to point X. CH2 will display the voltage across the resistor, V_R.

1e. Plug the Cable from the circuit board into the signal generator, again observing the grounding (GND tab on the side of the plug). Set the generator frequency to 5.0 kHz. **NOTE:** Setting the frequency generally requires setting two controls, a dial control and a range multiplier. The dial setting may be 0.5, 5.0, or 50.0, depending on the particular generator used. The multiplier will vary accordingly.

$$5.0 \text{ kHz} = 0.5 \times 10^4 \text{ Hz} = 5.0 \times 10^3 \text{ Hz} = 50.0 \times 10^2 \text{ Hz}.$$

1f. Set the oscilloscope to display CH1, both VOLTS/DIV dials to 200 mV, SEC/DIV to 50 μs, Trigger source to CH1, Trigger Mode to AUTO.

1g. Now turn on power for both signal generator and oscilloscope. If you do not see a trace try varying the vertical POSITION control above the CH1 dial, or the horizontal position control above the SEC/DIV dial.

If the screen shows multiple traces, vary the "TRIGGER LEVEL" knob slowly until it locks the trace onto a single sine curve.

Locate the "Amplitude" or "Fine" control on the signal generator and use it to set the amplitude of the trace to about 0.5 Volt, i.e. 2.5 divisions at 200 mV/div.

Part 2: Measuring frequency

Change the frequency of the generator to 6.0 kHz, and adjust the SEC/DIV so as to display a little more than one complete cycle. Measure the period of the signal, i.e. the distance between corresponding points on the curve times the SEC/DIV setting. You can use the horizontal and vertical POSITION knobs to position the trace under the most closely divided scales. Calculate the frequency from your measurement of the period. What is the percentage difference from the value set on the generator? This is an indication of the accuracy of the equipment.

Part 3: Measuring magnitude

There are three measures of the magnitude of the AC signal that are used. amplitude, rms (root mean square) and peak-to-peak (p-p). Center the sine wave vertically on the screen and adjust the output of the generator until the amplitude is exactly 0.5 V.

The voltage reading from the bottom to top distance is the p-p value. It is the fastest measuring technique when switching back and forth between signals.

On your data sheet: Sketch one cycle and indicate the distances that represent the amplitude and the p-p values, and record these values.
What is the relation between these two values?
Calculate the rms (effective) value of the signal you observed.

Part 4: Finding resonance

4a. Switch both traces on using the CH1 MENU and the CH2 MENU buttons. Adjust VOLTS/DIV and vertical shifts so that both generator and resistor signals are visible, and do not overlap. Slowly vary the frequency up to about 20 kHz, then scan down to about 2 kHz.

Note several changes: the phase between the two signals, the size of the resistor signal on CH2 (proportional to the current) and the variation in generator output on CH1.

4b. Adjust the frequency until the phases of the signals match. (You may want to overlap the signals to do this.) Note the generator frequency.(Record it as the resonance frequency by phase.) At resonance, the current and voltage in a series R-L-C circuit are in phase (see equation 4 with $\phi = 0$).

Part 5: Lissajous figure

This oscilloscope allows another way to observe resonance. If we set the Mode to XY (enter the DISPLAY menu and choose Format: XY) so that CH1 is depicted on the horizontal axis and CH2 on the vertical axis, we can observe Lissajous figures, which will be tilted ellipses for the sinusoidal signals present on both axes. You may have to adjust vertical and horizontal POSITION and the VOLTS/DIV dials to resize and center the pattern. Again, scan through the range of frequencies and note the variation in the display. Sketch and label the patterns at 2 kHz and 20 kHz. When the two signals are in phase, the pattern should become a straight line. Use this property of the Lissajous figure to find the resonance frequency again.

Part 6: Impedance

Leaving the frequency set at this last value, set V_0 to 0.5 Volts (1 Volt peak-to-peak on CH1) and measure V_R on CH2. You can switch between oscilloscope channels to observe each signal separately. Remember that V_R is proportional to the current I_0 . (Both V_R and V_0 can be left as p-p values, since the ratio is the same as for the amplitudes.) Calculate I_0 using the appropriate value of resistance, and calculate the magnitude of the impedance using equation 2.

Part 7: Taking a resonance curve

We will measure pairs of values of V_0 and V_R at different frequencies, so as to be able to plot a resonance curve as in Figure 2. Note that, as you saw in Part IV, the generator output changes with frequency, so that both values have to be measured for each frequency. The resonance curve is a plot of I_0/V_0 vs. frequency. Tabulate your data using the column headings shown below. Peak-to-peak (p-p) values are recommended, since we will take a ratio. (Note that I_0 involves only the resistance of the resistor, not the whole circuit.)

f (kHz)	V_0 (V)	V_R (V)	I_0 (A)	I_0/V_0 ($1/\Omega$)

Measure both V_0 and V_R at frequencies from 2.0 kHz to about 9.0 kHz. Note that in the central region, 5.0 kHz ... 7.0 kHz, steps of 0.2 kHz or 0.25 kHz (depending on the scale divisions of your signal generator) are required to follow the rapidly changing impedance. Larger steps can be taken outside of the central region.

Part 8: Measuring phase shift

If you still have time, set the frequency to 2 kHz. Make sure that the time base is in the calibrated position and set so that the screen shows 2 or 3 cycles of the signal on CH1. Measure the period of this signal. Now switch both channels on and measure the time between corresponding points on the two signals. Calculate the phase shift from the ratio of the time difference between the signals to the time of one period. Convert this to an angle in degrees.

ANALYSIS

1. Calculate the resonance frequency f_0 of the R-L-C series circuit, using the values on the bottom of the circuit board. Compare with the values measured in parts 4b. and 5. Compare the measured value of the impedance at resonance with the theoretical value.
2. Use your data to calculate the magnitude of the impedance Z of the circuit at one frequency in your data below 5 kHz. Compare with the values calculated from the circuit values. (Show your calculation.)
3. Plot I_0/V_0 against frequency. Include the points from part 6. Draw a SMOOTH curve that comes CLOSE to your data points. (See Figure 2 for a typical resonance curve.) This type of resonance curve is characteristic of many physical systems from atoms to radio receivers.

   The sharpness of the resonance is measured by the half-power points. These occur at 0.7071 (i.e. $1/\sqrt{2}$) times the peak value. Locate them on your graph. Label them f_1 and f_2, and record these values. Engineers use a Quality Factor Q to characterize the "sharpness" of a resonance, where
   $$Q = \frac{f_0}{f_2 - f_1}$$
   Calculate Q from your data. From equation 2, one can calculate a theoretical value:
   $$Q = \frac{2\pi\, f_0\, L}{R_{total}}$$
   How does this value compare with your calculated value?
4. If you did part 8, then compare with the theoretical value.

Questions (to be answered in your report):

1. Explain why the current I_0 in the circuit is a maximum at the resonance frequency f_0 .
2. Show that if the phase difference between the voltages V_R and V_0 equals 90°, the Lissajous figure would be an ellipse.

Electromagnetic Induction - A

APPARATUS

1. Two 225-turn coils
2. Table Galvanometer
3. Rheostat
4. Iron and aluminum rods
5. Large circular loop mounted on board
6. AC ammeter
7. Variac
8. Search coil
9. Oscilloscope Tektronix TDS1002 (see "Introduction to the Oscilloscope" on page 12)

INTRODUCTION

In this experiment we will produce an electric current by electromagnetic induction. We will demonstrate Faraday's law of induction and also Lenz's Law (conservation of energy). Qualitatively, we will show how the magnetic field $\vec{B}$ and magnetic flux Φ can be measured with the aid of a search coil.

According to Faraday's law, if the magnetic flux through a loop of wire is changing, there is an electric field induced. Consequently, an electric current flows in the loop. The magnetic flux Φ is given by $\Phi = B_{\perp}A$, where $B_{\perp}$ is the magnetic field perpendicular to the plane of the loop and A is the area of the loop. The product of the electric field E by the length of the loop ($2\pi rE$) is the induced voltage V_i (obsolete term: electromotive force). Faraday's law states that:

$$\begin{aligned} V_i &= const. \times \frac{d\Phi}{dt} \\ &= const. \times \frac{d}{dt}\left(B_{\perp}A\right) \end{aligned}$$

In Part I we shall verify some aspects of this law by observing the current induced in a coil of wire as a permanent magnet is moved (or held steady) near the coil.

In Part II the current in the coil of wire will again be observed, but the field at the coil will be caused by a current in another coil of wire held nearby. The variation in field can be caused either by moving the coils relative to one another or by varying the current in the coil which is setting up the field (see Fig. 2), in this part a study will also be made of the direction of the induced current (Lenz's Law).

In Part III the induced voltage will be observed with the aid of an oscilloscope.

Part I: Observation of induction using permanent magnet and coil

Connect a coil of wire to a sensitive galvanometer as shown in Fig. 1. If one pole of a bar magnet

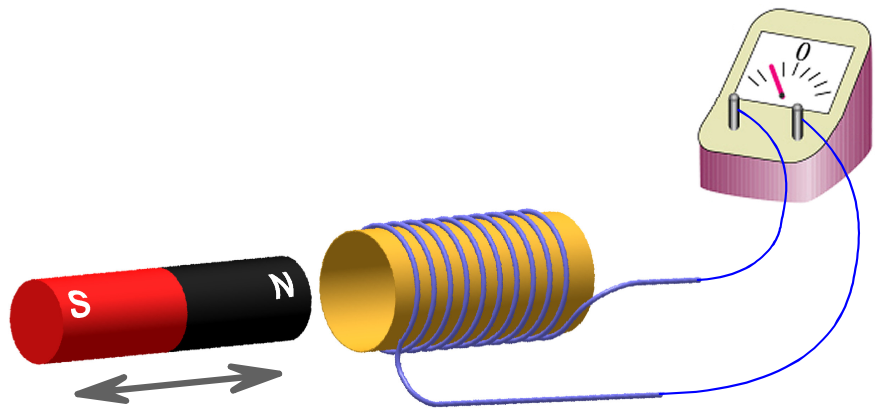


Figure 1: Electromagnetic induction with permanent magnet and coil.

is thrust into the coil, the galvanometer will deflect, indicating a momentary current in the coil. As long as the bar magnet remains at rest within the coil, no current is induced, if, however, the magnet is suddenly removed from the coil the galvanometer will indicate a current in the direction opposite to that at first observed.

The faster the motion of the magnet, the larger the induced current, as shown by larger deflection of the galvanometer. The discovery of this means of producing an electric current with a moving magnet led to the development of the electric generator.

Part II Lenz's Law

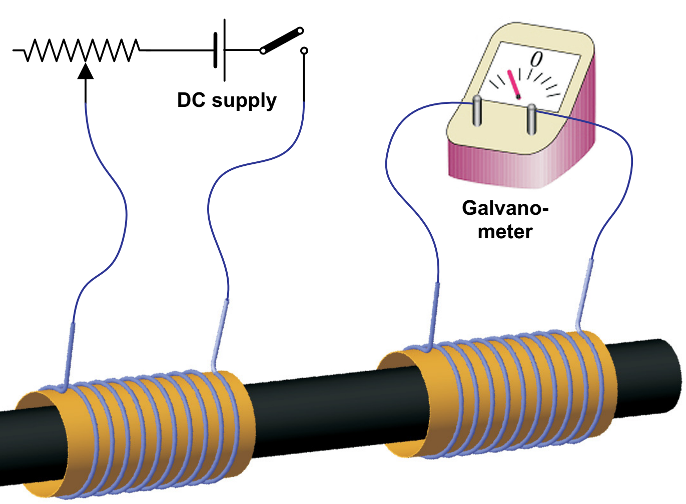


Figure 2: Electromagnetic induction with two coils.

Slide the two 225-turn coils on the iron rod so that their windings have the same sense of rotation around the coils. Connect one coil in series with the DC supply, the switch, and the small rheostat (see Fig. 2). From the battery polarity note the direction of current in the coil when the switch is closed. Connect the two terminals of the second coil directly to the table galvanometer. Note that for this galvanometer the needle deflects toward the terminal at which current is entering. Deduce the current direction in the second coil when the switch to the first coil is closed. Secondly, leave the switch closed for a while and then deduce the current direction in the second coil when the switch is opened.

Make a sketch similar to Fig. 2, showing the direction of the current in the second coil for the two cases and interpret by Lenz's Law.

As a demonstration of the effect of iron, repeat an observation of the galvanometer throw with the iron removed, but the coils in the same relative position to each other.

Part III: Observation of induction within a coil

In this part of the experiment we will demonstrate how the magnetic flux, and therefore the magnetic field $\vec{B}$, can be measured using a search-coil and an oscilloscope. If we have a coil of wire

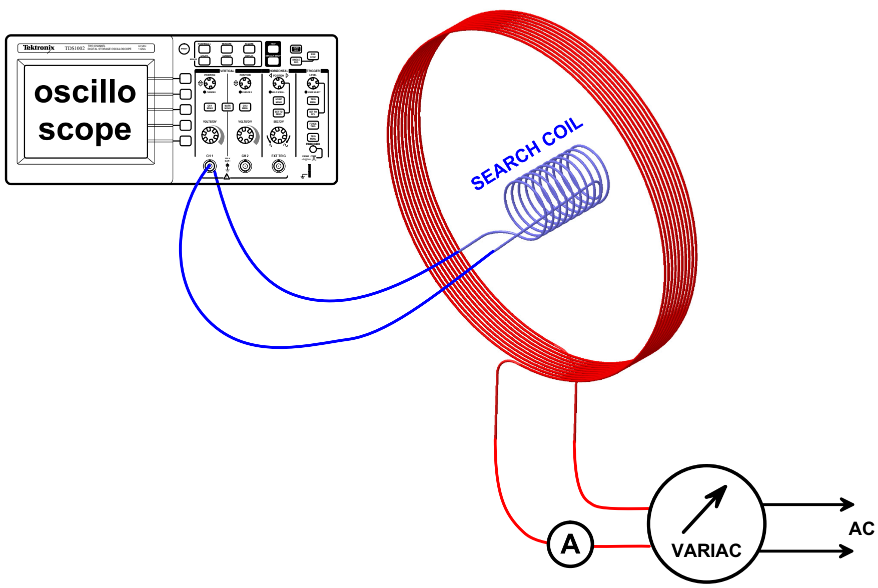


Figure 3: Electromagnetic induction within a coil.

connected in series with a galvanometer (Fig. 1), the galvanometer will show a deflection which is proportional to the rate of change of magnetic flux through the open area A of the loop. Such a loop is called a search coil. Thus, if we produce a varying magnetic field, and thus a varying flux, we can detect it using a search coil connected to a galvanometer.

A varying magnetic field is produced by a separate circuit, shown in Fig. 3, in which the current varies. We could therefore produce a varying magnetic field by using an alternating current (AC). The difficulty with this method, however, is that it produces a magnetic field which changes direction, and the galvanometer needle would have to change direction to either side of zero. For a 60-cycle signal, the galvanometer needle has to change direction 120 times each second. The galvanometer needle cannot respond that quickly and would therefore read an average zero signal. In order to avoid this difficulty, we replace the galvanometer by an oscilloscope which can record quickly changing signals.

If we connect the terminals of the search coil to the CH1 input of the oscilloscope, we will observe the trace as a sine curve. At any point on the time axis, the distance of the trace from the time axis is proportional to the induced voltage across the terminals of the search coil.

According to Fig. 3, a variac (autotransformer) is connected to the AC line and the output of the variac is used to feed the circuit which consists of a large coil in series with an ammeter.

Before turning on the power, check to see that the dial on the variac is set for a minimum value. After the power is on, slowly increase the setting until the AC ammeter reads 1 A. Note that the reading on the ammeter is affected by its proximity and orientation with respect to the large coil. Attempt to position the meter so that this effect is a minimum.

It can be shown that the amplitude of the flux through the search coil is proportional to the induced voltage V_i:

$$\Phi = k\ V_i$$

(a) Place the search coil in its holder at the center of the large coil. Adjust the current through the large coil to read 1 A. The search coil and the large coil must be parallel.

Keeping the search coil parallel to the plane of the large loop, measure the amplitude of the sine curve along the axis of the large loop at 0, 10, 20 and 30 cm from the center of the large coil and plot the amplitude vs. distance.

Note: Holes on the plate for placement of the search coil are spaced 5 cm apart.

(b) Place the search coil at the center of the large coil. Measure the flux (the amplitude of the sine curve) when the normal to the search coil makes angles 0°, 15°, 30°, 45°, 60°, 75° and 90° with the normal to the large coil.

Plot the flux (amplitude of the sine curve) vs. angle, and on the same graph show a plot of the amplitude of the sine curve at 0° multiplied by the cosine of the angle between normals of the two coils. Compare these two curves.

Question: How does the flux depend on the angle?

Electromagnetic Induction - B

APPARATUS

1. DC Supply line
2. Bar magnet, polarity unmarked
3. U shaped piece of iron
4. Two 225-turn short air core solenoids
5. Cenco galvanometer
6. 400-turn large induction coil
7. 1000-turn search (pick-up) coil
8. AC ammeter
9. Variac
10. Oscilloscope Tektronix TDS1002 (see "Introduction to the Oscilloscope" on page 12)
11. Switch
12. 8" x 10" linear graph paper (supplied by instructor)

INTRODUCTION

This experiment is divided into two parts; the first is devoted to exhibiting the phenomenon of electromagnetic induction in a qualitative manner. It includes a test of the student's ability to use Lenz's Law. The second part tests one's ability to measure the induced voltage V, generated in a search coil by a changing magnetic flux. The student will be expected to know and understand the expressions $B = \mu_0\, n\, I$ and $B = \frac{\mu_0\, N\, I}{2\, R}$ which refer to the fields inside a long air core solenoid and at the center of a circular loop carrying current, respectively.

Part A: Electromagnetic Induction and Lenz's Law

PROCEDURE

(1) Connect the terminals of one of the 225-turn coils directly to the galvanometer and observe what happens to the galvanometer needle as one end of the bar magnet is moved in and out of the coil. Record the letter which appears on one end of the magnet and determine by means of Lenz's Law whether this end corresponds to the north or south magnetic pole. In order to do this you must know
(a) the direction in which the turns have been placed on your coil
(b) that the fieldlines are continuous and that their direction external to the magnet is out from the north magnetic pole and into the south pole piece,
(c) that the galvanometer needle deflects to the right when the current enters through the right terminal and leaves through the left; the needle deflects to the left when the current direction is reversed.

(2) Leaving the galvanometer connected to the 225-turn coil, place it near the second 225-turn coil and connect the latter in series with a switch and the DC supply line. Is there any deflection of the galvanometer when the switch is closed or opened? **DO NOT LEAVE THE SWITCH IN THE CLOSED POSITION.** Without changing any electrical connections to the two coils arrange them side by side so that you can insert the U-shaped piece of iron into the coils. Now try closing and opening the switch. Can you explain your observation remembering that μ_0 in the formulae quoted in the introduction refers to coils placed in a region of space where there is only a vacuum (or air)? This arrangement of the two coils with no electrical interconnection is essentially a crude transformer. Explain why transformers are only used in AC circuits, where the current and voltage change with time.

Part B - Measurement of Induced Voltage

INTRODUCTION

Our problem is to measure the induced voltage V generated in a coil by a changing magnetic flux. From Faraday's Law we know that the voltage induced in a closed loop of N_1 turns through which the flux is changing is given by

$$V = N_1 \frac{d\phi}{dt} \tag{1}$$

where $N_1\phi$ i is the total flux passing through that loop. If the loop is small enough so that B is essentially constant over the area A_1 of the loop, then

$$\phi = B\ A_1\ cos\,\theta \tag{2}$$

whence

$$V = N_1\ A_1\ cos\,\theta\ \frac{dB}{dt} = N_1\ (\pi R_1^2)\ cos\,\theta\ \frac{dB}{dt} \tag{3}$$

where θ is the angle that B makes with the normal to the area. We will use a 1000-turn search coil having an average radius of $R = 2.5cm$.

The field B is generated by a large 400-turn coil (i.e. $N_2 = 400$) carrying a 60 Hz AC current I, given by

$$I(t) = I_0\ sin\,\omega t = I_{rms}\ \sqrt{2}\ sin\,\omega t \tag{4}$$

where $I_{rms} = I_0/\sqrt{2}$ is the reading of the ammeter and $\omega = 2\pi f = 120\pi$. The factor $\sqrt{2}$ is present because the peak value of the current is that much greater than the RMS value which the ammeter gives.

If the search coil is placed near the large coil, an emf or voltage will be induced in the search coil. If the large coil has a current, given by equation 4 then there will be a magnetic field at the center of the large coil (see Introduction). Thus, if the search coil is placed at the center of the large coil, there will be a (changing) magnetic flux in the search coil, and the amplitude of the induced voltage will be given by

$$V = N_1\ \pi R_1^2\ \frac{\mu_0 N_2}{2R_2}\ I_{rms}\ \sqrt{2}\ \omega\ cos\,\theta \tag{5}$$

where N_1, R_1, N_2, and R_2 are the number of turns and radius of the small and large coils, respectively, whereas θ is the angle between the direction of B and the normal to the area of the small coil. It has been assumed that the frequency of the current is 60 Hz (60 cycles per second), so that $\omega = 2\pi\ 60$ Hz.

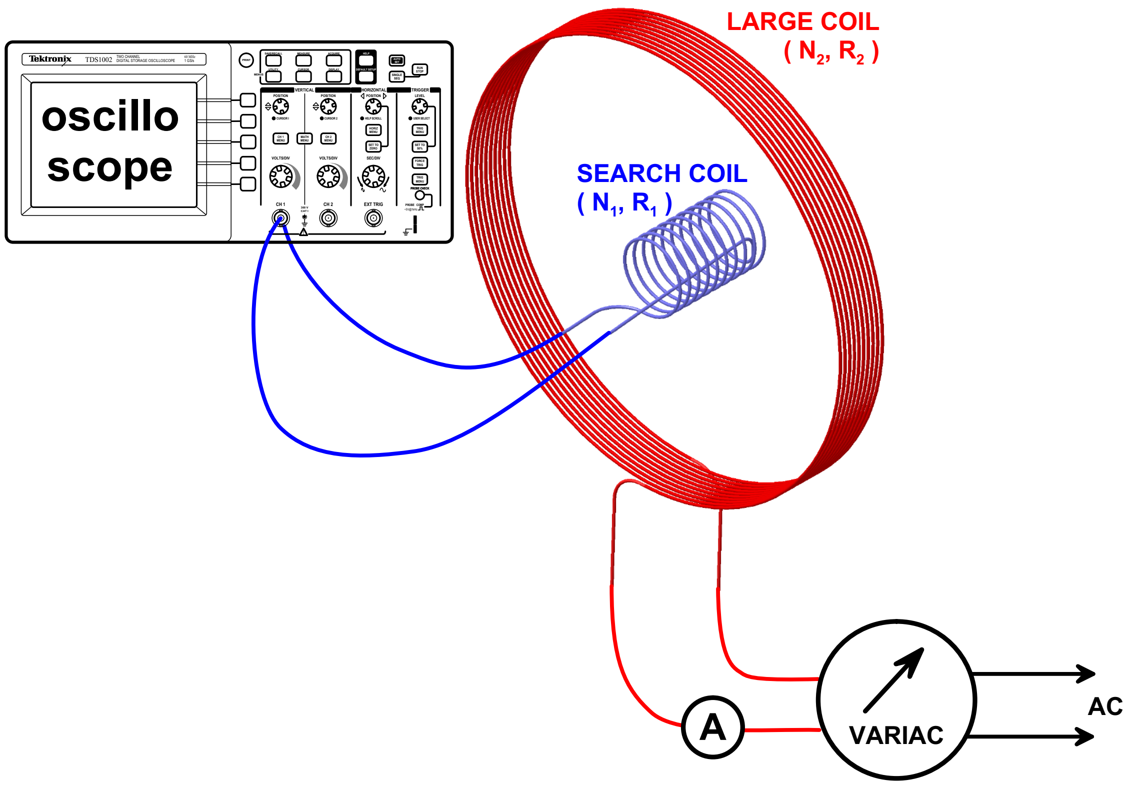


Figure 1 Entire Apparatus.

PROCEDURE

Note: Holes on the plate for placement of the search coil are spaced 5 cm apart, Diameter of large coil is 48.40 cm.

The variac, which is a device for controlling the AC voltage , should be connected in series with the large coil and an AC Ammeter. Before turning on the power, check to see that the dial on the variac is set for a minimum value. After the power is on, slowly increase the setting until the AC ammeter reads 1 A. Note that the reading on the ammeter is affected by its proximity and orientation with respect to the large coil. Attempt to position the meter so that this effect is a minimum.

Now connect the leads from the search coil to the oscilloscope.

1. Place the search coil in the center of the large coil and record the voltage for various angles of orientation front 0 to 90 degrees.

2. Record the voltage for various positions along the axis of the large coil being careful to keep the planes of the two coils always parallel.

ANALYSIS

1. Compare the observed voltage with the computed value of the induced voltage from equation 5 when the search coil was placed at the center of the large coil. Plot the observed voltages against the angles and compare this curve with a cosine curve.

2. If time permits, plot the induced voltage against the displacements along the axis. Is this curve consistent with the appropriate formula in your text?

Questions (to be answered in your report):

1. Explain why the ammeter reading was affected by the large coil.

2. What error is there in assuming $\phi = B\ A\ cos\,\theta$?

3. Use Faraday's Law and the equation for the flux at the center of a large circular loop to derive equation 5. What is the mutual inductance K for the search coil and the large coil?

Interference of Light

APPARATUS

1. Board for mounting glass plates.
2. Two plane parallel plates of glass.
3. Aluminum stand equipped with a lens, a mirror inclined 45, and an index.
4. Mercury arc lamp and a sodium light source.
5. Microscope with a traveling stage and an adjustable "mirror".
6. Cylindrical cartridqe containing a glass plate and a lens.

On the instructor's desk:

7. Paper and metal shims

At the sink:

8. Soap, water and tissues for cleaning glass plates. Do not put the cylindrical cartridges in water.

INTRODUCTION

When light is reflected from the two surfaces of a very thin film of varying thickness, an interference pattern is produced. Wherever the two reflected waves are in phase, bright areas appear. Where the difference in phase is one-half wavelength, dark areas are produced.

Part I: Air Wedge

Let two flat sheets of glass be separated slightly at one edge, Fig. (1a). If H is of the order of a millimeter or less and the wedge is viewed by reflected monochromatic light, bright interference fringes may be observed. Interference occurs between the waves reflected from the top and bottom of the air wedges. Fig. (1b) illustrates the geometry.

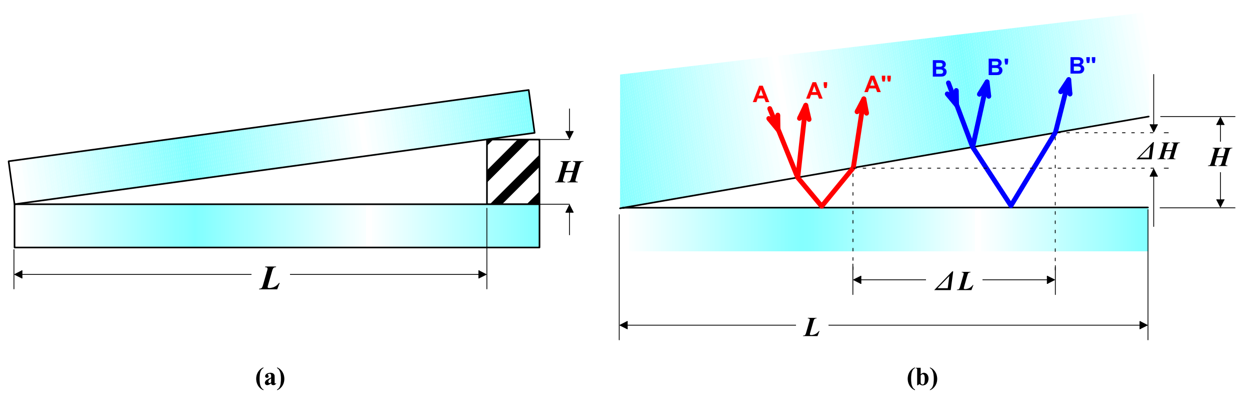


Figure 1: Principle of interference at a thin air wedge.

The ray A produces two reflected rays A' and A". Suppose that A and B correspond to two adjacent dark (or bright) areas. Then

$$2\,\Delta H = \lambda \tag{1}$$

where λ is the wavelength of the light. Consideration of the geometry leads to the conclusion that

$$\frac{H}{L} = \frac{\Delta H}{\Delta L} \tag{2}$$

A little thought also shows that if N bright (or dark) fringes are counted in a length L_1, then

$$\Delta L = \frac{L_1}{N} \tag{3}$$

Substituting (1) and (3) in (2), we obtain

$$\lambda = \frac{2\,H\,L_1}{L\,N} \tag{4}$$

Part II: Spherical Lens and Flat Plate ("Newton's Rings")

If a long focal length lens is placed in contact with a flat plate one may obtain an interference pattern consisting of a series of concentric bright and dark fringes. Fig. 2 illustrates this case.

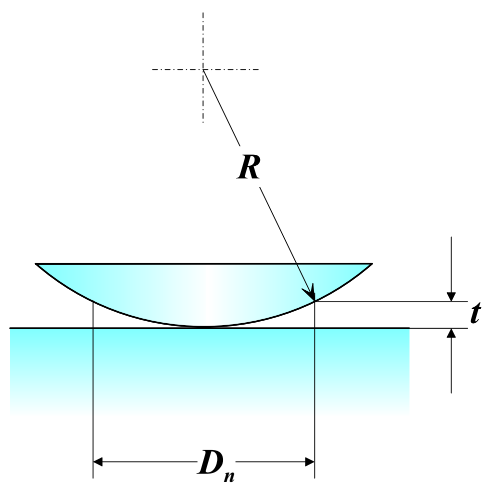


Figure 2: Principle setup for the observation of Newton's rings.

R is the radius of curvature of the lens, t is the thickness of the air wedge at the n$^{\text{th}}$ fringe and D_n is the diameter of the n$^{\text{th}}$ dark ring. The center null is counted as zero. From equation (1) above follows that

$$t = \frac{n\,\lambda}{2} \tag{5}$$

You should be able to prove that

$$D_n^2 = 4\,n\,\lambda\,R - n^2\,\lambda^2$$

Since λ is a very small quantity, we may neglect $n^2\lambda^2$ in comparison with $4n\lambda R$. Therefore, to a high order of precision

$$\lambda = \frac{D_n^2}{4\,R\,n}$$

PROCEDURE

Part I: Air Wedge

Examine the two large glass plates. Note the frosted surfaces and the lines which are ruled 1 cm apart. Arrange the plates and the black stand on the board to produce the situation illustrated in Fig. (3). Place the frosted surfaces down with the ruled lines on the inside. Use a thin strip of paper as a separator. Place the sodium lamp nearby and arrange the geometry so that the light of the lamp is reflected to the eye of the observer (Fig.(3)).

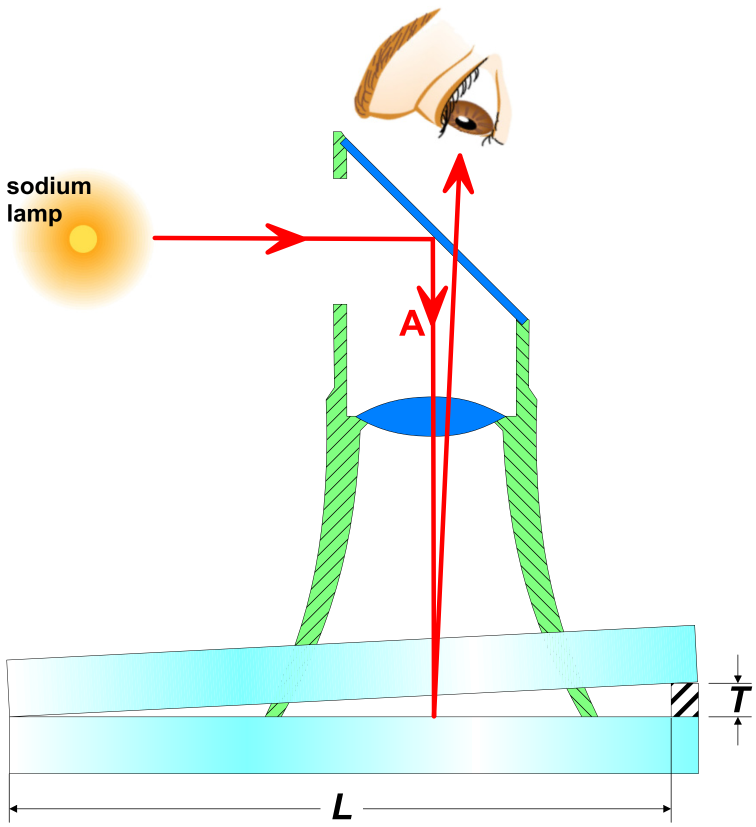


Figure 3: Setup for observation of interference fringes at two glass plates.

The image of the lamp should be crossed by parallel closely spaced bright and dark fringes. Ideally these will be straight, parallel, and evenly spaced. If lines do not appear, make sure the frosted sides are facing the correct way. If they still cannot be seen, remove the plates and wash them thoroughly with soap and water. Free them of all finger prints and lint and reassemble the system. If the pattern is diagonal, press firmly on one corner and release. Do not expect perfection, but arrange the system in a way that you are able to reasonably count the fringes.

1. Make a sketch showing the appearance of the fringes
2. Count the number of dark fringes in 2 cm. It will be helpful if you move the viewing frame as you count, so as to make use of the pointer to keep your place.
3. Measure the length of the air wedge L. The thickness of the paper will be given to you by the lab instructor.
4. Then apply equation (4) to calculate the wavelength.

Part II: Spherical Lens and Flat Plate (”Newton’s Rings”)

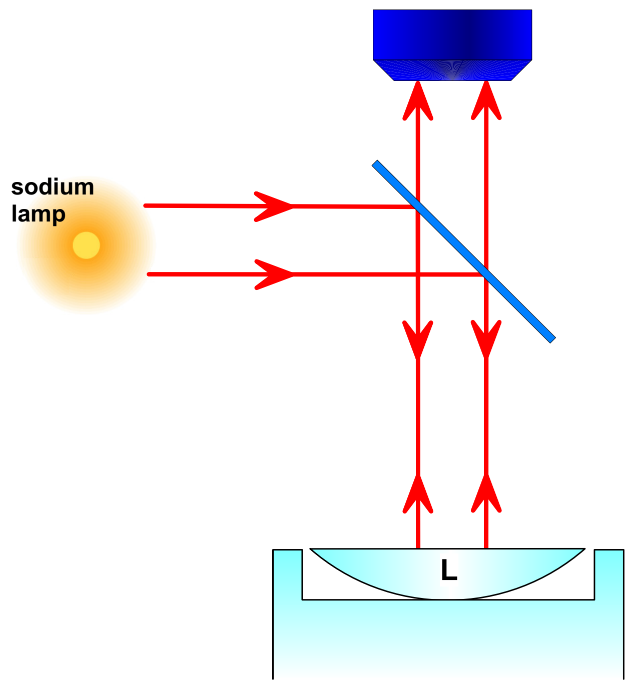


Figure 4: Setup for observation of Newton’s rings.

1. Position the Sodium lamp to the left, with the micrometer aligned to the edge of the table to the right. Turn the lamp ON and allow it to warm up for several minutes. Use this time to answer the question: Why is equation (5) true ?

2. Position the telescope at the **top** of its travel, and orient the glass disk so that light from the lamp illuminates the lens capsule as seen through the telescope. You may have to rotate the base slightly to compensate for a drooping disk.

3. Focus the telescope by lowering it slowly. Stop when you see the interference pattern. Align one of the cross hairs so that it is parallel to the micrometer barrel, if possible.

4. Rotate the lens cell until the pattern is aligned with the cross hairs. You may have to move the stage by turning the barrel of the micrometer. If possible, center the pattern. Question: Is the center of the pattern as bright as the ring surrounding the center? Why? (It is rarely completely dark due to contamination at the glass surfaces.)

5. Translate the stage to the first dark ring by turning the micrometer to **smaller** values. Record the position. (Use the light and the magnifier to examine the micrometer scales, refer to notes on the micrometer caliper in the introduction on page 10.)

6. Proceed to the second dark ring by rotating the micrometer barrel in the **same** direction. Record the position. Continue to rings 3, 5, 7, and 10. If time permits, continue by 3s.

ANALYSIS

1. Plot the positions of the rings against the square root of the ring number.

2. Draw the best fit straight line through your data points.

3. Determine the slope of the straight line you drew. Question: What is the algebraic relation between the slope and the radius of curvature? ($D_n = 2(X_{center} - X_n)$, where X_n is the micrometer value for the n$^{\text{th}}$ dark ring.

4. Determine the radius of curvature of the lens from your value for the slope.
   (Na: $\lambda = 589$ nm)

Part III

If a filter for the green line of the mercury spectrum is available, arrange the mercury lamp and filter so as to observe the interference pattern. Measure a number of positions of the dark rings in order to calculate the wavelength, using the value for R that you found with the sodium lamp.

Linear Momentum

APPARATUS

1. The equipment shown in Figure 1.
2. Steel sphere.
3. Waxed paper.
4. A 30cm ruler.
5. Equal arm balance and known masses.
6. Meter stick.
7. Dowel rod to free stuck sphere from block.

INTRODUCTION

The principle of conservation of linear momentum is to be tested as follows: a steel sphere is allowed to slide down the track, and immediately after leaving the end of the track plunges into a hole in a wooden block and becomes stuck within the block. The block, which is suspended by four strings, is initially at rest, but swings as a pendulum because of the impact. The momentum of the sphere before the collision is compared to the momentum of the sphere and block just after the collision.

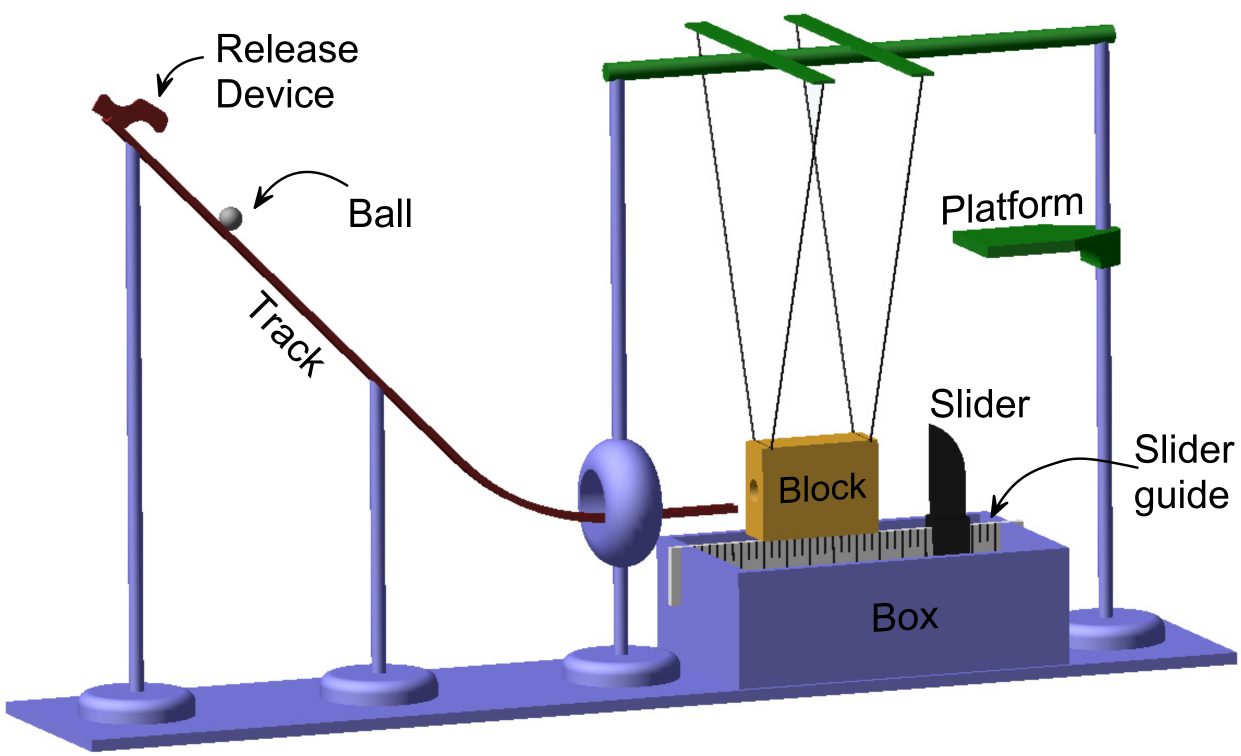


Figure 1: Entire Apparatus.

NOMENCLATURE:

m	mass of the steel sphere, [g].
M	mass of the wooden block, [g].
v	velocity of the center of the sphere as it leaves the track, [cm/s]
V	common velocity of sphere and block immediately after impact, [cm/s]
s, h, x, y, b, r	various distances, indicated in Figures 2,3, and 4, all [cm]

PROCEDURE

Part I: Determination of the Velocity of the Sphere Before Impact

Place the block on the platform, where it will he safely out of the way. Remove the slider guide and slider from the box (See Fig. 4) and clamp a strip of waxed paper to the floor of the box. Allow the steel sphere to roll down the track from its highest point. It will fall into the box and leave an imprint. The end of the track is horizontal.

Determine the height b, through which the sphere falls; be aware that the track is a channel, and the lowest point of the sphere is below the upper edges of the channel.

Make ten or more trials, and find the average value of the range r. From these data, calculate the time of flight, and the velocity of the center of the sphere as it leaves the track.

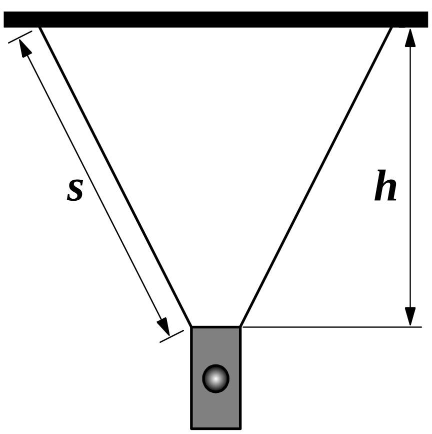


Figure 2: Front view of the block.

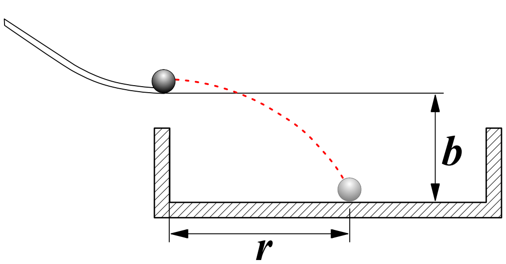


Figure 4: Determination of the steel sphere's velocity.

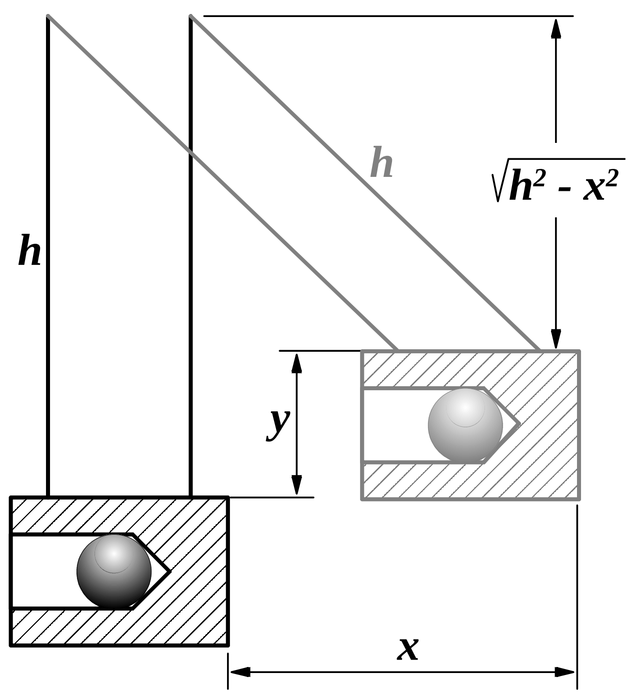


Figure 3: Side view of the block.

Part II: Determination of the Velocity of Sphere and Block After Impact.

Determine the mass of the steel sphere. Also record the mass of the wooden block, which is inscribed on the block.

Mount the slider guide and slider in the box. Suspend the block as indicated in Figure 1 at the appropriate level such that the faces of the block are parallel to the corresponding faces of the box. The block should hang freely, with a gap of about 1/8 inch between it and the track. The block must be perfectly still while awaiting the arrival of the sphere.

Measure the distance h. Notice that when the block swings, the suspension inhibits rotation (see Figs. 2 and 3). The horizontal distance x, through which the block swings after impact must be measured (see below), and the vertical distance y is calculated from (see Fig. 3):

$$y = h - \sqrt{h^2 - x^2}$$

and, from energy considerations

$$V = \sqrt{2gy} \tag{1}$$

To determine x, first position the slider so that it is barely touching the stationary block, and record this distance setting as read from the slider guide. Next, perform a few trial runs until you succeed in positioning the slider such that for ten successive impacts the block at the end of its swing sometimes just barely flicks the slider, and at other times just barely fails to reach it. Note the position of the slider and calculate x.

Calculate the linear momentum of the system before impact (mv) and after impact ($[m + M]V$), and compute the relative difference (in %). Within the limits of your experimental accuracy, is momentum conserved during the collision?

Questions (to be answered in your report):

1. Derive Equation (1), starting from general physics principles.
2. From your results, compute the fractional loss of kinetic energy of translation during impact. Disregard rotational energy of the sphere.
3. Derive an expression for the fractional loss of kinetic energy of translation in terms only of m and M, and compare with the value calculated in the preceding question. Consider the collision as a totally inelastic one.

Motion Detector Lab

Introduction:

In this lab you will use a motion detector, hooked up to a computer to gain experience in interpreting “position *vs.* time” and “velocity *vs.* time” graphs. The motion detector uses sound waves to find the distance of an object in front of it at different times. This information is fed into the laptop which uses the software provided to plot the information in real time.

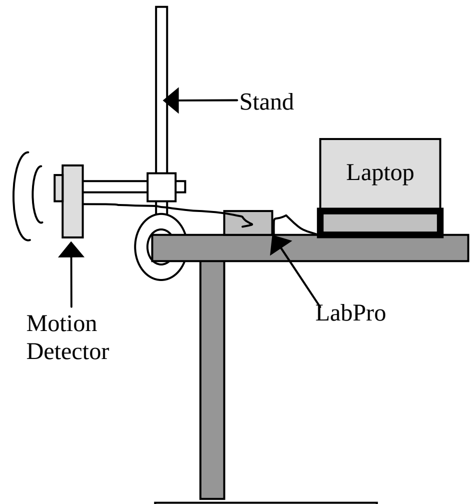


Figure 1

Setup:

Make sure that both the computer and motion detector are switched on and that the software is running. Take a few minutes to familiarize yourself with the software. Here are some important points:

1. To change number of graphs, go to the *View* menu and select *Graph Layout*.
2. To change the type of graph, click on the **y-axis label**.
3. To change the range of either axis, click on the axis and type in the maximum and minimum value **OR** click on the last number at either end of the axis.

Part 1: Familiarization with the Detector

1. Set the program to display only one *position--time graph*.
2. Set the range of the Time axis to: 0 to 4 seconds.
3. Set the range of the Distance axis to: 0 to 2.5 meters
4. Have one person stand in front of the detector and have someone else push the *Collect* button in the progam. Start to walk back and forth in front of the motion detector when it starts to make noise.
5. **Important:** There is a *minimum* and *maximum* distance for which the detector will work. By moving back and forth, find the *minimum* and *maximum* distances.
6. Try collecting data a few times just to get some experience with this setup. Give everyone in the group a chance to try it out.

Part 2: Position-Time Graphs

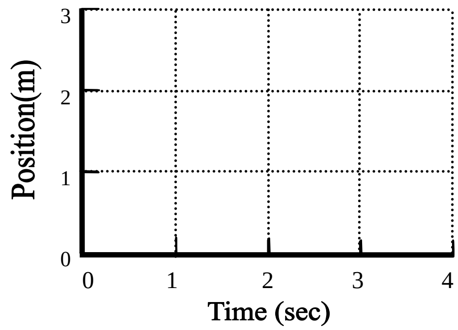
1. For each question below:

i. sketch a prediction of the *position-time* graph in the space provided

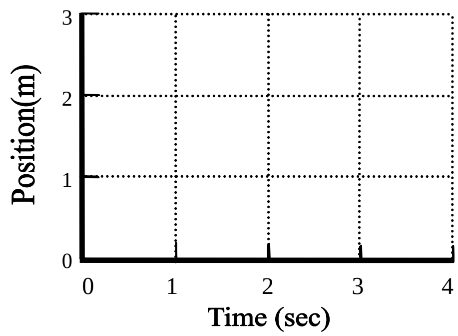
ii. produce the graph using the motion detector and sketch the result on the same graph in a different color.

Important: do not sketch the entire graph produced by the computer, just sketch the relevant part of the graph

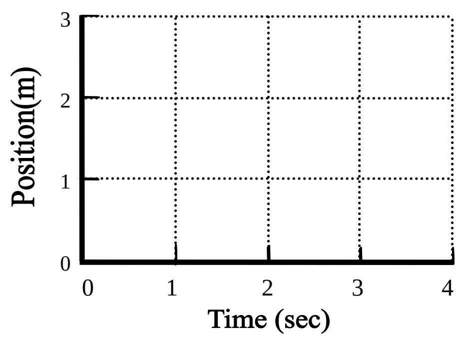
a. Start at about ½ **meter** from the detector and walk away from the detector ***slowly* and *steadily*.**



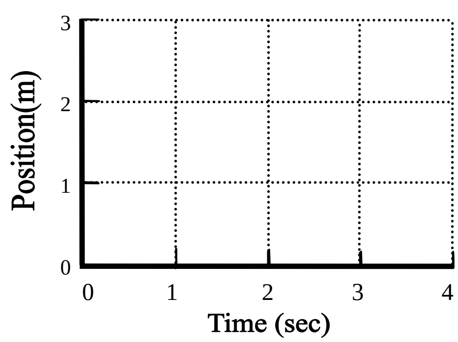
b. Start at about ½ **meter** from the detector and walk away from the detector ***quickly* and *steadily*.**



c. Start at the **2 meters** from the detector and walk towards the detector ***slowly* and *steadily***.



d. Start at the **2 meters** and walk towards the detector ***quickly* and *steadily*.**

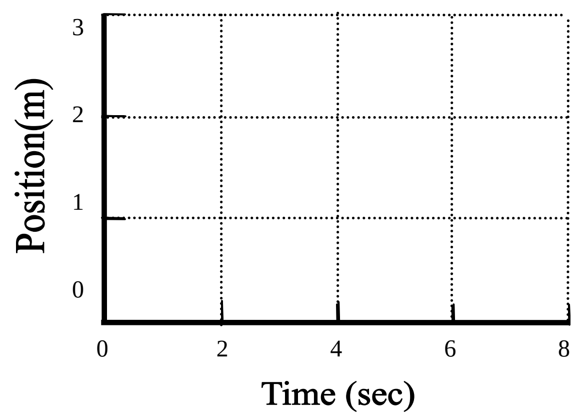


2. **Question:** How does the graph made by walking towards the detector *slowly* compare with the graph made by walking towards the detector *quickly*?

3. **Question:** How do the graphs made by walking towards the detector compare with graphs walking away from the detector?

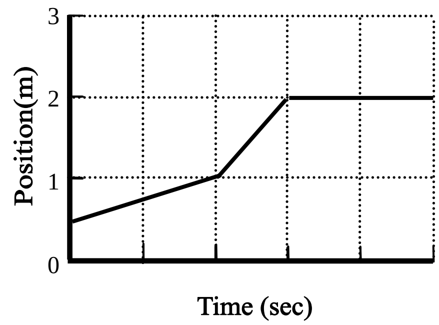
4. Predict the *position-time* graphs for the situation described below. Sketch your predictions in the space provided and compare your prediction with the rest of your group. Next, produce the *position-time* graph using the motion detector and sketch the result in a different color.

   a. Start at about ½ meter from the detector
   b. Walk away from detector ***quickly* and *steadily*** for 1 second
   c. **Stop** for 2 seconds
   d. Walk towards detector *very* ***slowly* and *steadily*** for 2 seconds



5. **Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature __________**

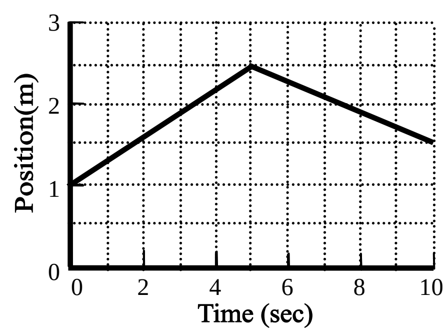
6. Write down in words the steps necessary to qualitatively produce the *position-time* graph shown on the right.



7. Try several times to re-produce the *position-time* graph shown above.

8. Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature _________

9. (**207 labs only**) For the graph on the right, use the slope to find the velocity:



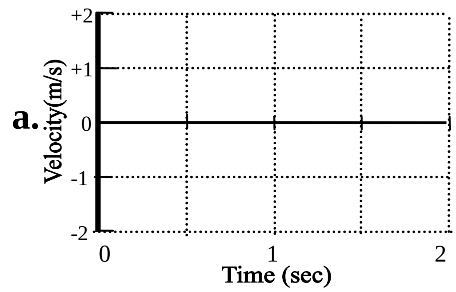
a. during the first 5 seconds

b. during the last 5 seconds

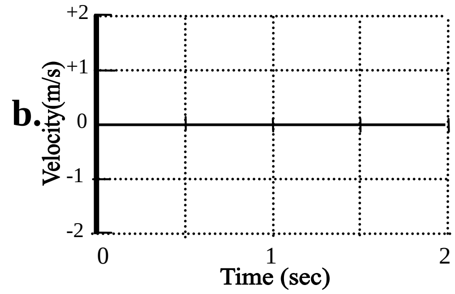
Part 3: Velocity-Time Graphs

1. Change the graph to display only Velocity-time graphs with a velocity range from -2.0 m/s to 2.0 m/s.
2. Make *velocity-time* graphs for each of the types of motion described below. In each case, try producing the graph several times and sketch a reproduction of the graph in the space provided.

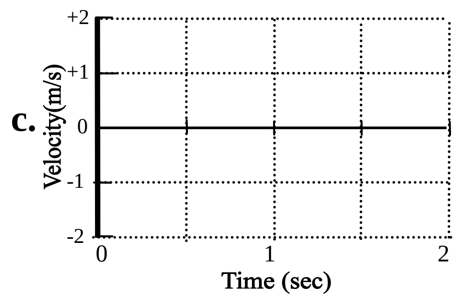
    a. Start at about ½ **meter** from the detector and walk away from the detector ***slowly* and *steadily***.



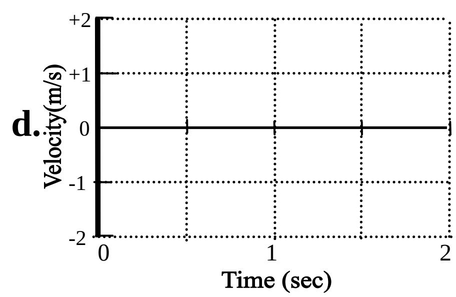
    b. Start at about ½ **meter** from the detector and walk away from the detector ***quickly* and *steadily***



    c. Start at **2 meters** and walk towards the detector ***slowly* and *steadily***.



    d. Start at the **2 meters** and walk towards the detector ***quickly* and *steadily***.



3. **Question:** What is the difference between graphs made by walking **away *slowly*** and walking **away *quickly***?

4. **Question:** What is the difference between graphs made by walking **steadily *away*** *from* the detector and **steadily *towards*** the detector

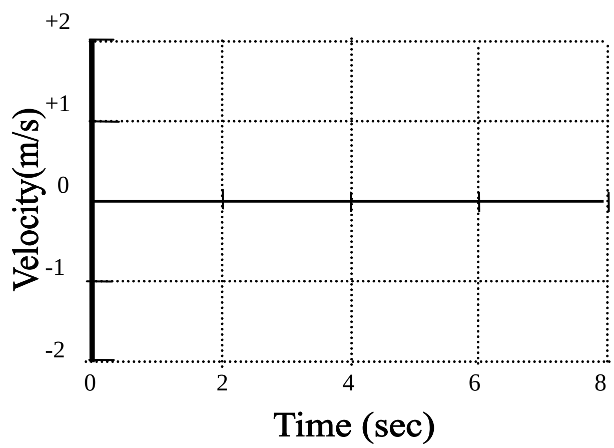
5. **Important: Show and explain the your answers to the last 4 Questions to the TA and get a signature before moving on: TA Signature __________**

6. Predict the *velocity-time* graph produced by the following motion and sketch your prediction in the area provide below. Then perform the actions and sketch the result in a different color.

a. Start at the **2.5 meters** and walk towards the detector ***quickly* and *steadily*** for 1 second

b. **Stop** for 2 seconds

c. Walk away from the detector ***slowly* and *steadily*** for 2 seconds

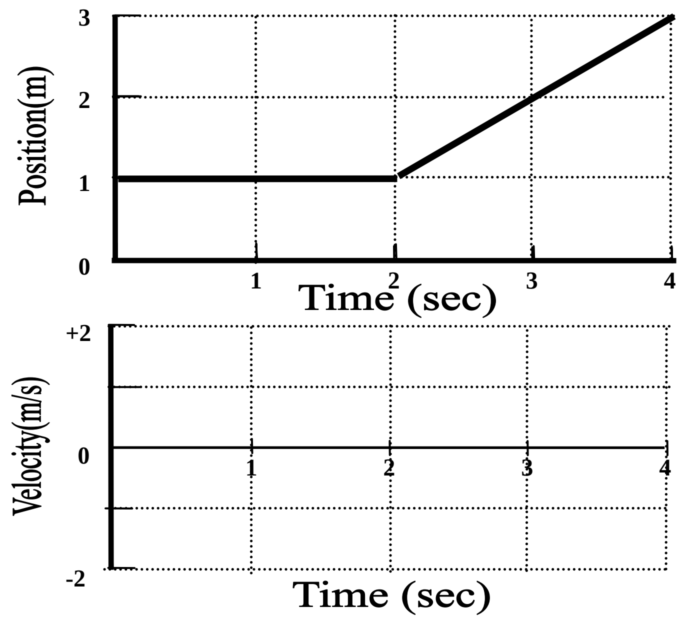


7. **Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature _________**

Part 4: Position-Time and Velocity-Time Graphs

Now we will relate *position-time* graphs to their corresponding *velocity-time* graphs.

1. Change the program to display 2 graphs, one for *position-time* and one for *velocity-time*. Set the range on both axes to be the same as the graphs below.
2. Predict the *velocity-time* graph that corresponds to the *position-graph* below, sketch it in the *velocity-time* graph provided.

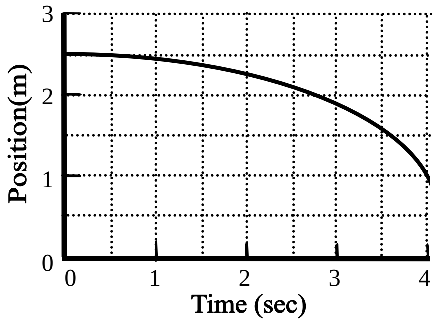


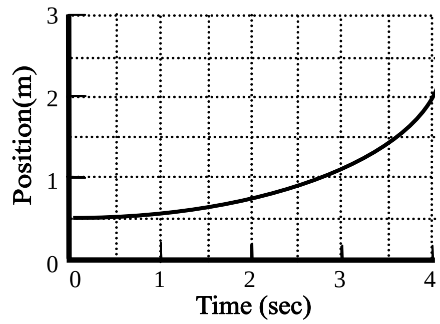
3. Now use the motion detector to reproduce the *position-time* graph above as closely as possible. Sketch the corresponding *velocity-time* graph using different color on the same graph as your prediction (do not erase your prediction).
4. **Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on:** TA Signature __________
5. **Question:** How would the *position-time* graph be different if you moved faster or slower?

6. **Question:** How would the *velocity-time* graph be different if you moved faster or slower?

Part 5: Acceleration

1. Use the motion detector to reproduce the curved line *position-time* graphs below as best as you can.





2. Describe how you moved to produce the 2 graphs.

3. **Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on:** **TA Signature __________**

4. (**207 labs only**) For the first graph, estimate the velocity at the following times: (HINT: use the slope of the tangent)

   a. t=0

   b. t=3

5. (**207 labs only**) For the first graph, estimate the average acceleration between t=0 and t=3 seconds.

Part 6: Qualitative questions

1. How can you tell from a *velocity-time* graph that the object has changed direction?

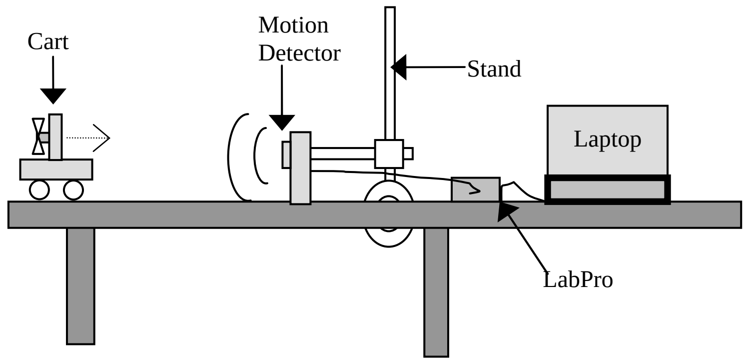
2. How can you tell from a *position-time* graph that the object has changed direction

3. How can you tell from a *velocity-time* graph that your velocity is constant?

4. How can you tell from a *position-time* graph that your velocity is constant?

Part 7: Final question

1. Get a fan propelled cart from the TA and set up the motion detector to collect data for the cart's motion as it movies toward the detector as show in the diagram below.



2. Produce a *Position vs Time* and *Velocity vs. Time* graphs for motion of the cart accelerating towards the detector and sketch them in the space provide below.

3. Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature __________

4. (**207 labs only**) From the graph on the computer calculate the acceleration of the cart. Explain how you found the acceleration and show your work.

Meters - Ohm's Law

APPARATUS

1. Board on which two wires are mounted, each 1 m long, equipped with a sliding contact
2. Rheostat (variable resistance), $0 \ldots 7\ \Omega$
3. DC ammeter (full scale: 2 A)
4. Voltmeter (full scale: 3 V)
5. Switch
6. Wire and plug to DC supply
7. Board on which two wire wound resistors are mounted

INTRODUCTION

The ammeter is an instrument which measures the magnitude of an electrical current. A direct current (DC) is a uniform flow of electrical charges through a conductor. If an amount of charge ΔQ passes through a cross-section of a conductor in time Δt, then the current I in the conductor is given by:

$$I = \frac{\Delta Q}{\Delta t}$$

The International System of Units (SI) unit of charge is the Coulomb. The SI unit of current is the Ampere; it is equal to a rate of flow of one Coulomb per second. The ammeter is always connected in series with the conductor in which the current is to be measured (see Fig. 1).

A number of pieces of apparatus are said to be connected in series if they are so arranged that there is only one path for the current to take; the same current must flow successively through each piece. This type of connection and the parallel connection are both shown below.

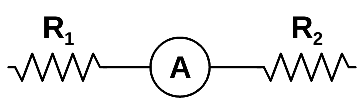


Figure 1: Series connection.

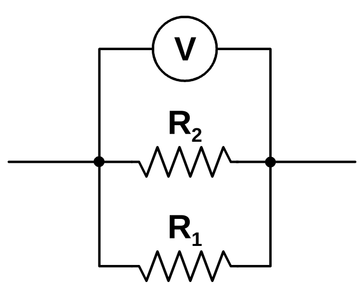


Figure 2: Parallel connection

The voltmeter measures the potential difference (voltage) between its terminals. The voltage between two points A and B is defined as the work done in moving a positive charge from A to B divided by the magnitude of the charge. The SI unit of the voltage is called the volt; it exists between two points when one Joule of work is required to transfer one Coulomb of charge. The voltmeter is always connected in parallel with the circuit element across which the potential difference is to be measured (see Fig. 2).

The positive electrode of the DC supply is connected to the blue lead of the DC power cord, and the negative electrode to a brown lead. By convention, the direction of current from a DC supply is from the positive to the negative electrode, through the external circuit. The meters should be connected so that the current will enter the binding post on the meter marked plus (see figure 3). The symbol used to designate a DC supply has two parallel lines where the longer line represents the positive electrode.

Suppose the potential difference V between the two ends of a conductor is varied and the current I is measured. Experiment shows that for many materials

$$\frac{V}{I} = const. = R$$

where R is called the resistance of the conductor. When V is expressed in Volts, and I is expressed in Amperes, R is expressed in Ohms(Ω). The above equation is known as Ohm's Law.

A conductor whose electrical resistance is large enough to be taken into account is called a resistor and denoted by a sawtooth symbol as in figure 3. A connecting wire has such a small resistance that it maybe neglected in most laboratory work. The symbol for a connecting wire is a straight line. The two 100 cm long straight wires, mounted on a board have a resistance that cannot be neglected, unlike the copper connecting wires.

PROCEDURE

Part I: Current in a Series Circuit

A. Connect the apparatus as shown in Fig. 3. Close the switch and note the value of the current on the ammeter. Open the switch, remove the ammeter from the position shown in the figure and place it in turn in positions B and C. For each position, note the current when the switch is closed.

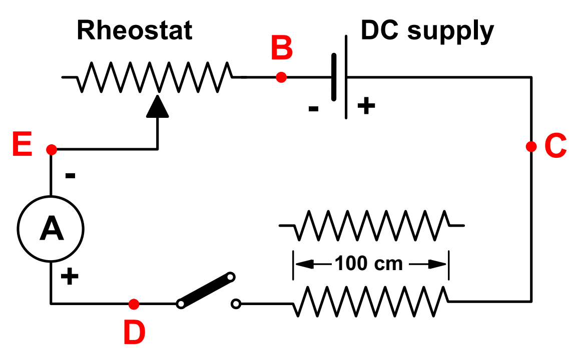


Figure 3

Question 1: When the currents at the original position of the ammeter and positions B and C in this circuit are compared, what conclusion may be drawn? [Note: A variation of a few percent may be experienced.]

B. Vary the position of the knob of the rheostat and note the effect on the current. Make a sketch of the rheostat showing the position of the knob for minimum resistance (largest current), and for maximum resistance.

Part II: Potential Difference in a Series Circuit

A. Using the circuit shown in Fig. 3, set the contact of the rheostat at some intermediate position and close the switch. Connect the voltmeter across each part of the circuit (BC - the DC supply, CD - the resistance wire, DE - the ammeter, and finally EB - the rheostat).

Question 2: How does the sum of the voltmeter readings of the external circuit compare with that across the DC supply ? Express the difference in %. Is it reasonable?

B. Using the same circuit, connect the voltmeter between the 0 cm end of the wire and the sliding contact. Be sure that there is no contact with the wire until one of the knobs is pressed.

Adjust the rheostat until the current is 0.5 A. Measure the potential difference between the 0 cm end of the wire and each of the 10 cm marks, that is, at 10 cm, 20 cm, 30 cm, etc. Plot your readings with voltmeter readings on the Y-axis and lengths on the X-axis.

Question 3: What does the graph show about the wire?

Part III: Ammeter-Voltmeter Method of Measuring Resistance

A. Connect the DC supply, the switch, rheostat, ammeter and the two mounted wire-wound resistors in series as shown in Fig. 4. Measure the potential difference across each resistor separately, and across the two in series. Note the ammeter reading.

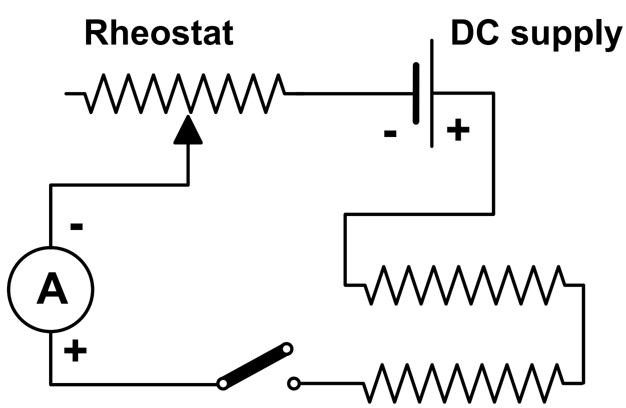


Figure 4

B. Repeat **A.** using two different values for the current. Compute the resistance of each resistor for each current and the resistance of the series combination from the data taken in (A) and (B).

Question 4: How does the sum of the individual resistances compare with the resistance of the combination?

Part IV: Resistors in Parallel

A. Connect in series the DC supply, the rheostat, the ammeter, the switch, and the two wire wound resistors in parallel as shown in Fig. 5. Measure the current when the ammeter is placed, successively, at the shown position and at the positions marked B and C.

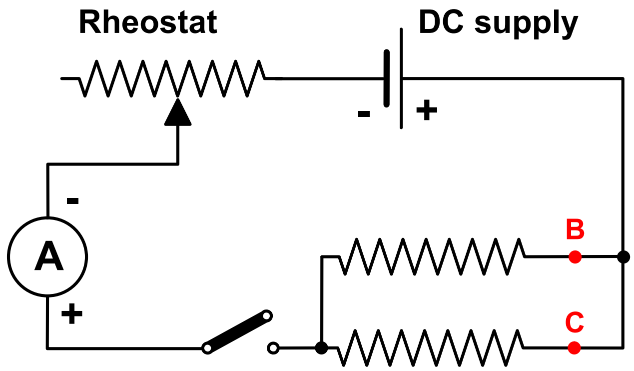


Figure 5

B. Repeat for one other rheostat setting.

Question 5: How do the meter readings at B and C compare with that at the original position shown in Fig. 5? What conclusion can you draw?

C. Measure the voltage across the parallel combination. This voltage divided by the total current through the combination is called the equivalent resistance of the combination. Letting R_1 and R_2 represent the individual resistances and R_{eq} the equivalent resistance of the combination, verify from your results the relationship:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

Oscilloscope and RC Circuits

APPARATUS

1. Tektronix Oscilloscope TDS1002 (see ”Introduction to the Oscilloscope” on page 12)
2. Signal Generator
3. Electronic Voltmeter
4. Circuit Board (1 kΩ Resistor, 1 μF Capacitor - values approximate)
5. D. C. Power Cord

INTRODUCTION

This exercise consists of three parts:
(A) exploration of some properties of the oscilloscope,
(B) the charging and discharging of a capacitor as observed using the oscilloscope, and
(C) the measurement of the impedance of an electronic voltmeter by use of a capacitor discharge.

Study the circuit of Figure 1 and note that the switch can be connected to positions S1 or S2.

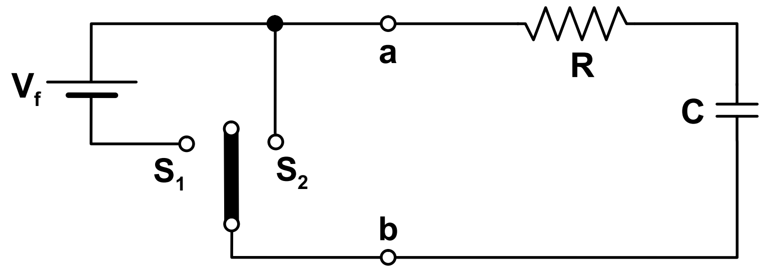


Figure 1: Circuit for charging/discharging a RC network

When you discuss RC circuits in class, you will study the charging and discharging of a capacitor in some detail. For our purposes, the following may be taken as experimental facts. When the capacitor in Figure 1 is initially uncharged and the switch is connected to S1 at $t = 0$, then the potential difference V across the capacitor C will increase with time according to:

$$V = V_f \left(1 - e^{-t/RC}\right)$$

where V_f is the constant supply potential. If after a time that is sufficiently long for V to approach V_f, the time is reset to t=0 and the switch is connected to S2, then V decreases with time according to

$$V = V_f \left(e^{-t/RC}\right)$$

In this case V decreases exponentially with time. Note that at $t = RC$, for both exponential rise and fall, the voltage has changed by approximately 63% of the maximum change (1/e = 0.37). This time, RC, is called the time constant of the circuit, and denoted by τ . If the switch is moved alternately between S1 and S2 and back at a steady rate, then a square voltage wave would be applied across a-b. The voltage across the capacitor then would rise and fall exponentially. We will observe this by replacing the switch and battery by the signal generator and connecting the oscilloscope across the capacitor.

PROCEDURE

Part A: Exploration of the oscilloscope

1. Note the channel to which the cable has been connected. Set the corresponding trace to ON, using the CH1 MENU and CH2 MENU buttons. Other settings: SEC/DIV = 1 ms; VOLTS/DIV = 1 V

2. If you do not see a trace on the screen, then vary the POSITION of the corresponding trace. If no trace is seen, check the TRIGGER MENU, whether the trigger is set to AUTO. If still no trace is seen, check with your instructor. Vary the vertical and horizontal POSITION so that the trace lies along the center grid line and begins at the left edge of the grid.

3. Set the SEC/DIV to 10 ms and observe the behavior of the trace. Repeat at a setting of 100 ms. Describe your observations.

4. Connect the brown (ground) wire from the D.C. power cord to the black (ground) lead from the oscilloscope. Plug the D.C. power cord into the special socket. TOUCH the blue lead of the power cord to the red lead from the oscilloscope, **momentarily**. Repeat. Describe what you observe and explain.

5. Repeat 4 with the SEC/DIV set to 1 ms. Describe your observations. Why is the pattern so different from your previous observation?

6. Unplug the D.C. power cord and disconnect it from the oscilloscope. Set SEC/DIV to 10 ms and VOLTS/DIV to 100 mV. Describe the pattern that appears. Touch the red input wire with your finger and find the time between neighboring positive peaks. What is the frequency of this signal? What might be its source?

7. Set SEC/DIV to 1 ms and VOLTS/DIV to 1 V. Connect the signal generator so as to obtain a SQUARE WAVE, being careful to observe that GROUND leads are connected together. Connections vary with the type of generator: see the notes on Signal Generators at the end of the "Introduction to the Oscilloscope" section. Set the signal generator to a frequency of 100 Hz. This requires setting two controls, a frequency dial and a range (or multiplier). Note that 100 Hz = 1.0×10^2 Hz = 0.1 kHz.

8. Turn power ON for the signal generator. Adjust the AMPLITUDE of the generator until you get a pattern that is 5 divisions high on the screen. You may have to adjust the TRIGGER LEVEL knob on the oscilloscope to get a stable display.

9. Adjust the frequency of the signal generator until you get one complete cycle of a square wave on the screen. Wiggle the TRIGGER knob until the beginning of a cycle starts at the left of the screen. How much of a difference is there between the frequency setting of the signal generator and the frequency as calculated from the oscilloscope settings and display?

10. Turn OFF the signal generator, but do NOT alter any other settings on the generator or oscilloscope. These will be needed for part B.

Part B: Charging and discharging of a capacitor

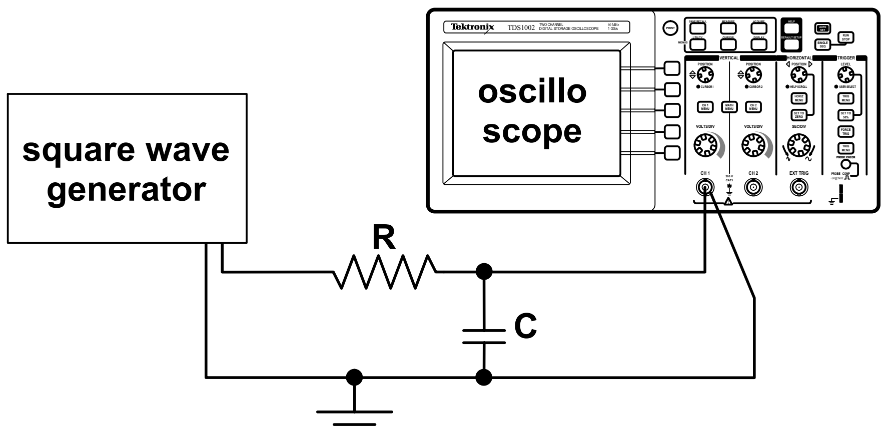


Figure 2: Measuring the characteristics of a RC network

1. Wire the circuit of Fig. 2 using the circuit board. Be careful to connect the GROUND terminal of the signal generator to the GROUND terminal of the oscilloscope. If in doubt, consult your instructor. Turn on the signal generator and increase the amplitude until you see a pattern with an amplitude of about 5 divisions on the oscilloscope.

2. Since you have left the frequency settings on the oscilloscope and signal generator unchanged from Part A, the pattern should just fill the grid, but it may be necessary to adjust the vertical position. You should see both the charging and discharging of the capacitor.

3. Sketch the pattern, showing a number of times and voltages.

4. Estimate the time constant of the RC circuit from your observations. Describe your reasoning.

5. Compare your value with that calculated from R and C. (The value of C in μF (microfarads) is marked, while the value of R has to be determined from its color coding. Assume that the only uncertainty is due to R (tolerance band) and compare the two values of the time constant. Do they agree?

Part C: Impedance of an electronic voltmeter

1. Turn off the signal generator and the oscilloscope. Remove the capacitor from the circuit.
2. Measure the terminal voltage of the DC leads from the special outlet using the electronic voltmeter. Be careful with any loose leads.
3. Charge the capacitor by connecting it for about a second to the DC leads. Be sure that the wires are not permitted to touch. Disconnect and unplug the DC leads from the outlet.
4. Connect the electronic voltmeter across the charged capacitor. When this connection is made, you have an RC circuit similar to Fig. 1 with switch S2 closed and R the resistance of the voltmeter. You can now measure the voltage as a function of time. Devise a method to estimate R. Indicate your result and describe your method.

Radioactivity

APPARATUS

1. Geiger Counter / Scaler
2. Cesium-137 sealed radioactive source
3. 20 pieces of paper
4. 8 aluminum plates
5. 10 lead plates
6. Graph paper - log-log and semi-log
7. Survey Meter (1 unit for the lab)

INTRODUCTION

This experiment will introduce you to some of the properties of radioactivity and its interaction with matter, and principles used in shielding from exposure to radiation.

The source used is small (about 1μCi) sealed in plastic, and not hazardous when handled carefully. (1 Curie = 1 Ci = 10^{10} decays per second.)

The radioactive source for this experiment is $^{137}\mathrm{Cs}_{55}$, which decays primarily to an excited state of $^{137}\mathrm{Ba}_{56}$ by emitting a beta(β)-ray (an electron) and an anti-neutrino. The excited barium loses energy by emitting a gamma(γ)-ray (a photon of high energy).

Symbolically:

$$^{137}\mathrm{Cs}_{55} \longrightarrow {}^{137}\mathrm{Ba}^{*}_{56} + {}^{0}\mathrm{e}_{-1} + \bar{\nu} \qquad \text{with a half-life of 30 years}$$

followed by

$$^{137}\mathrm{Ba}^{*}_{56} \longrightarrow {}^{137}\mathrm{Ba}_{56} + \gamma(662 \text{ keV}) \qquad \text{with a half-life of 2.6 minutes.}$$

Note that in the original reaction, called a β-decay, one neutron is replaced by a proton and an electron (the β ray) is emitted. Since a third particle, an anti-neutrino $\bar{\nu}$ is emitted, the electron carries off a variable fraction of the total energy of 510 keV.

The radiation emitted from the source consists of two types, (β-rays and γ-rays. Both can produce ions in the gas contained in the Geiger-Müller tube. A high electric potential between the central wire and outer cylindrical electrode of the Geiger-Müller tube accelerates any ions produced so that they, in turn, can produce further ions. This results in a surge of current and a signal in the external circuit. As soon as the ions are cleared, the tube is recharged and is ready to detect another ionizing event.

PROCEDURE

Part I: Start up

Plug the sealer into the AC socket, and turn it on. Set the voltage to 300 V. Sign out a source from your instructor. The same student should sign it back in.

Place the source in a plastic slide with the side marked TOP facing up.

Place the slide in the highest slot, closest to the detector. Wait 5 minutes before proceeding.

Part II: Radiation Intensity vs. Distance

A. Locate the START/STOP and RESET switches at the right side of the scaler. Starting the counter engages a timer that will stop the counting after one minute. The reading is then the intensity in Counts Per Minute (CPM). DO NOT PRESS STOP until after you have recorded the intensity. (It produces some electrical noise that increases the count) If the sealer doesn't count, increase the voltage in 50 V steps. At the point you begin to obtain counts, increase by another 50 V and leave it set at that point.

Do not exceed 450 V.

You should have at least 4000 CPM in the top slot. If not, check that the correct side is up. Consult your instructor if flipping the source over doesn't help,

B. Set up a data table with the following headings:

Slot	Count 1 [CPM]	Count 2 [CPM]	Average [CPM]	Distance [cm]
...	...	...	...	...

We take the average of two readings to reduce the variation due to the random nature of the radioactive decay process. The highest slot is 1 cm from the detector and each slot is 1 cm further away. Take readings at each of the six slot positions

C. We expect the intensity N, at distance r to decrease from N_1, (the intensity in the highest slot, at a distance of 1 cm from the source) following a power law:

$$N = N_1 \, r^{-n} \tag{1}$$

By using logarithms we can transform equation 1 into a straight line of slope $-n$:

$$log\,(N) = log\,(N_l) - n\,log\,(r)$$

To avoid having to actually compute the logarithms, we use log-log graph paper. Each graph line is positioned at a distance proportional to the logarithm of the numerical value indicated by the scale. For example, the distance from 1 to 2 is 0.30 times the distance from 1 to 10, since log(2)=0.30.

You must choose the power of 10 for each decade on the logarithmic scales. Graph your data on the log-log paper.

D. Draw the single straight line that best fits your data points. A transparent straight edge (like a plastic ruler) is helpful. Finding the slope of this line is a three step process:

- Select two widely separated points on the straight line (not data points) and record both sets of values (N_1, r_1) and (N_2, r_2).
- Take the logarithms of all four values.
- Calculate the slope:

$$n = \frac{log\,(N_1) - log\,(N_2)}{log\,(r_1) - log\,(r2)}$$

QUESTION 1: If the radiation is emitted uniformly in all directions, i.e. equally over the surface of a sphere surrounding the source, what would he the value of n in equation (1)? Hint: The detector can be considered a small disk of area A on the spherical surface at a distance r.

E. To compare our experimental value of n with the theoretical one you found above, we need to determine the uncertainty in the experimental value. This is especially difficult in this experiment. At large N (over 10,000 CPM) we may lose counts because some radiation arrives before the Geiger-Müller tube, has recharged from the previous count (the "dead time"). At small N (under 100) many of our counts may be due to cosmic rays ("background radiation"). Moreover, since our detector has a cylindrical shape rather than a that of a flat disk, there is a variation in the distance from the source that can vary over a few millimeters. Experience with this equipment has shown that the uncertainty in the experimental value of the slope is about 8% of the expected value. Determine the uncertainty Δn, using this value.

Compare your value with the theoretical value by calculating the uncertainty ratio,

$$UR = \frac{|n - n_{theory}|}{n}$$

A small value of UR (less than 1) indicates excellent agreement, while a large value (greater than 5) indicates disagreement. Intermediate values raise questions that may be difficult to resolve without repeating the experiment.

How well does your value for n agree with theory?

Part III: Absorption of Radiation by Matter

A. Place the shelf with the source in the fourth slot from the top. Place the absorber holder in the third slot. Record the intensity for two successive periods, and its average N_A , This reading will be included in each subsequent graph, but may not fall on the line that fits the remainder of the data.

B. Paper: Set up a table with headings:

m	Count 1 [CPM]	Count 2 [CPM]	Average [CPM]
1	...	...	...
2	...	...	...

Place one sheet of paper (m = 1) on the absorber holder. Record two one minute counts and compute the average. Repeat for 2, 4, 8, 13, and 18 sheets of paper. Since each interaction of the radiation with atoms in the material is a separate event, and each electron or γ-photon absorbed reduces the number that pass through the next layer of material, we expect the intensity detected after passing through m sheets to follow the relation:

$$N = N_0 e^{-km}$$

where the attenuation constant k involves the thickness of the paper and the density of electrons in the material. (Most of the interactions between this radiation and matter primarily involve electrons.) Taking logarithms:

$$log\,(N) = log\,(N_0) - k\ m\ log\,(e)$$

This is again a straight line, but now we need to plot a logarithm against a number. To simplify this process we use semi-log paper, that has one set of graph lines at distances proportional to the logarithms and the other set uniformly spaced.

Choose appropriate powers of 10 for the logarithmic scale, noting that the reading from paragraph A, N_A (for m = 0) will also be plotted, and values m = 0 to 18 span the linear scale.

C. Aluminum: Remove the paper and place one aluminum plate on the absorber shelf Start a new section of your data table under the same headings. Record two counts and their average. Repeat for 2, 4, 8, and 12 plates.

Plot your data on the same graph as the paper, using the same scale for m. Draw the best straight line that fits the data. Do not include N_A. Do draw the line all the way across the graph.

QUESTION 2: Why does the straight line for aluminum intersect the left axis (m = 0) at a point well below N_A? Hint: What kind of radiation is emitted from this source?

D. Lead: Remove the aluminum and place one sheet of lead on the absorber shelf. Start a new section of the data table. Record two counts and their average. Repeat for 2, 4, 6, and 9 sheets of lead. Since the thickness of the lead sheets is TWICE the thickness of the aluminum, m is DOUBLE the number of lead sheets when we plot it on the same graph.

Plot your data and again draw a straight line that fits the data. (Label each line at the right.)

QUESTION 3: How does the intersection with the left axis compare with that for aluminum? Why?

QUESTION 4: Which is the better absorber of the penetrating type of radiation? How do your graphs indicate this?

QUESTION 5: We might suppose that the absorbing power of a material depends on the density of atoms rather than electrons. A material of density ρ, atomic mass A, and atomic number Z, has a density of atoms proportional to ρ/A, and a density of electrons proportional to $Z\rho/A$.

	ρ [kg/m^3]	Z	A
Aluminum	2,700	13	27
Lead	11,300	82	207

Compare the ratios of atomic density and the electron density for the two materials. Which is more consistent with your observations?

Part IV. The Survey Meter

Get the survey meter.

Turn the control knob to HV (High Voltage ON). The needle should move to HV. Turn to the $\times 100$ scale. (Scale readings need to be multiplied by 100.) Place the Cesium source on the table, with TOP showing. Bring the probe as close as possible. Reduce the scale ($\times 10$ or $\times 1$) until a reading is obtained and record it. (Remember the multiplier) Units are mr/h = milliroentgen/hour.

Hold the probe about 10 cm from the source. Record the reading. Take another reading far away from any sources, the "background". How effective is a distance of 10 cm in shielding from the Cesium source?

Sign the source back in.

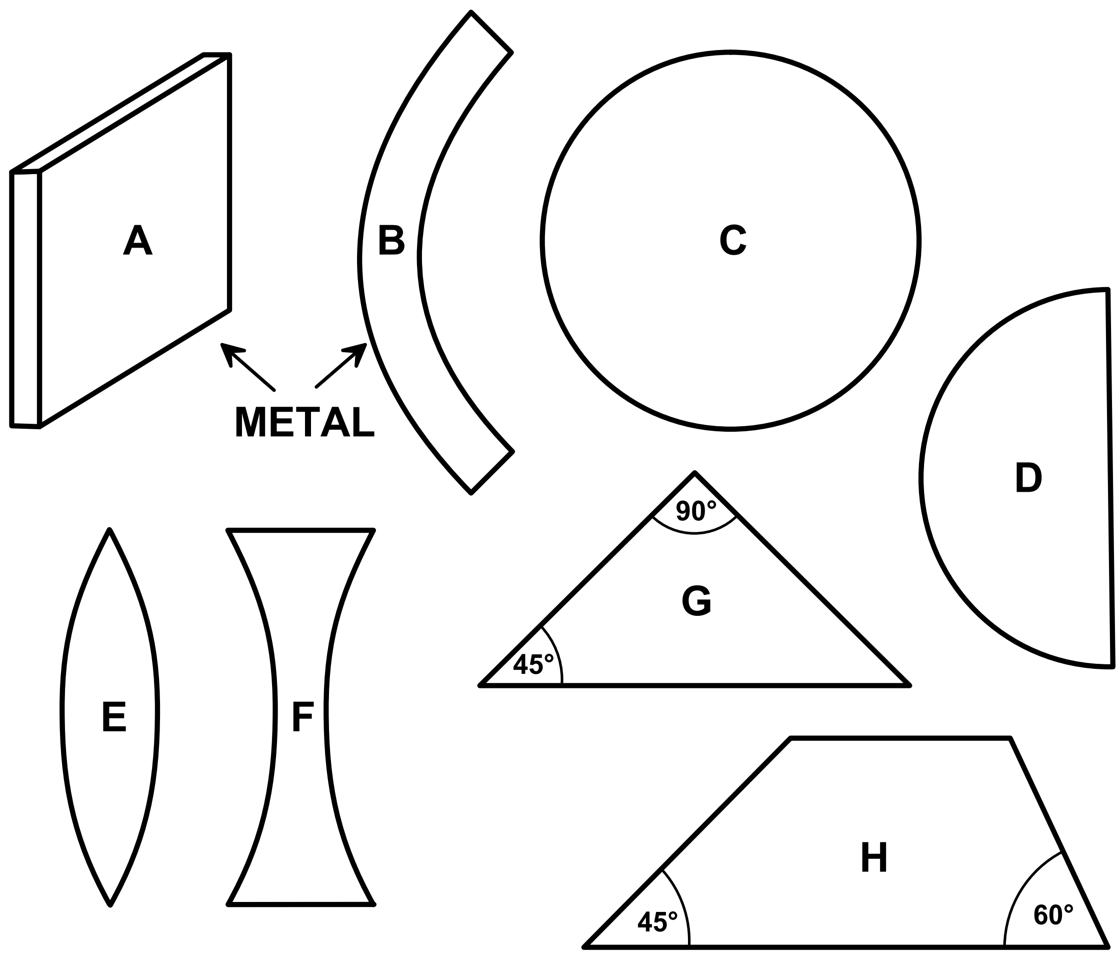
Reflection, Refraction, Dispersion

APPARATUS

1. A lamp housing containing a tungsten filament lamp and a lens which when properly adjusted with respect to the source will produce a beam of parallel light.

2. A drawing board on which a plate with five parallel, vertical slits is mounted. On the board side of this plate are two movable shutters which can control the number of exposed slits. On the source side of the plate there are channels to hold filters.

3. A box containing a red filter, a blue filter and the following optical parts: (letters have been assigned to these parts and these will be referred to by the appropriate letter in the following directions).



The bottom surface of each glass piece (C through H) is frosted; thus the path of a beam will be visible as it passes through the piece. Caution: Handle optical parts with care, keep surfaces clean. Use only the lens paper supplied to clean them. Keep all parts in their proper compartments in the box when they are not in immediate use.

INTRODUCTION

The following exercises illustrate the basic behavior of light rays undergoing reflection and refraction in simple mirrors, lenses etc. All of these effects follow from Snell's law and the law of reflection which may be taken as empirical rules.

Before coming to the laboratory read the chapters in your text which relate to reflection, refraction, mirrors and lenses.

PROCEDURE

Place the lamp housing with its lens about an inch from the slits. Place a piece of white paper on the board, [Lens paper may be obtained from the instructor's desk.)

Expose all five slits to the source. Adjust the position of the source relative to the board so that all five beams are visible on the paper, are parallel to each other, are perpendicular to the slit plate, and are approximately of equal intensity.

To record the path of a beam use a sufficient number of pencil dots (not dashes) so that later a line can easily be drawn through them. **Always mark the outline of the optical part on the paper.** Use a sharp pencil point.

Part I: Regular Reflection from Plane Mirror (A)

Adjust shutters to allow only one beam to fall on the paper. Place (A) at some angle relative to the beam. Record the path of the incident beam, and of the reflected beam. Draw a line to represent the reflecting surface. Repeat for another angle of incidence. For both cases, measure the angles of incidence and reflection, Check the law of reflection. Show your work.

Part II: Reflection from Concave Mirror (B)

Allow three adjacent beams to fall on the concave surface of (B). (Note: you are on the concave side of a spherical mirror when you are "inside" the sphere, and on the convex side of the mirror when you are outside the sphere. Thus, for mirror B shown on the first page of this experiment the concave side is the right side and the convex side is the left side). Move (B) until the central beam is coincident with the principal axis of (B). [Thus, this center beam will pass through the center of curvature "c" of the mirror.] Trace the paths.

QUESTIONS FOR PART II

1. What name is given to the point of intersection of the rays reflected from (B)?
2. Find the distance of this point of intersection from (B), What is this distance called?
3. How is the distance related to the radius of curvature of the mirror, (See your text)

4. Challenge: From plane geometry we know that for a circle the perpendicular bisector Of any chord will pass through the center of the circle. Draw two chords on the circular arc B, draw their perpendicular bisectors, and find the center of curvature for the arc B. Find the radius of the circular arc B, and compare the radius with the focal length you found above. Does the ratio of radius to focal length agree with that given in the text?

Part III: Reflection from Convex Mirror (B)

Repeat Part II but place (B) with its convex surface facing the source. (Extend the reflected beams back to find the point of intersection). Find the focal length. How is the focal length related to the radius of curvature. Check your result against theory.

Part IV: Refraction through Parallel Surface (H)

Allow a single ray to fall at the midpoint of the long side of (H) Make the angle of incidence approximately 30°. Trace the path of the beam as it passes through and emerges from the glass. Apply Snell's law to find the index of refraction from the refraction at both surfaces of the glass. Show your work.

Part V: The Critical Angle (D) for Total Internal Reflection

Allow one ray to fall on the curved surface of (D). Adjust the position of (D) until the ray inside the lens passes through the center of the plane surface of (D) and emerges on the opposite side, why doesn't the ray bend when it enters the glass? Now rotate (D) about the above center in a direction so as to increase the angle of incidence at the plane surface. What happens to the emergent beam? Continue rotating until the critical angle for glass is reached at the plane face. Observe the emergent beams, noting the colors and the change of intensity when the critical angle is reached. Measure the critical angle and determine the index of refraction for glass. Compare this value with those obtained in Part IV. Increase the angle of incidence at the plane surface further. Record the direction of the beam as it leaves this surface. Measure the angle it makes with the normal to the surface. Compare with the angle of incidence.

Part VI: Refraction through a Double Convex Lens (E)

Allow 3 adjacent beams to fall on (E), Have the center beam lie as closely as possible on the principal axis of the lens. Upon emergence the beams will intersect at a point. What is the point called? Measure its distance from the center of the lens segment. Locate this distance when a blue filter is introduced. Repeat with a red filter. Account for any shift in the position of the point of intersection.

Part VII: Refraction through a Double Concave Lens (F)

Repeat Part VI using (F), omitting the filters.

Part VIII: Spherical Aberration

Place (E) on the board as above but expose it to all 5 beams. Record carefully the directions and intersections of the emergent rays. Repeat with (F), Discuss briefly what is observed in both cases and give an explanation.

Part IX: Totally Reflecting Prism (G)

Allow 3 beams to fall on prism (G). Place (G) in position relative to the beam so as to change the direction of the beams by 90°. Now place (G) so that the beam direction is changed by 180°. Trace each case. Number the beams and note that the prism inverts their order.

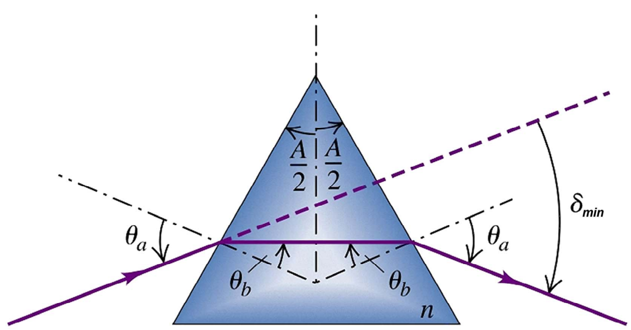
Part X: Deviation due to a Prism (H)

Use the 60° angle as the angle of the prism. Trace the path of light through the prism for incident angles of approximately 35°, 45°, and 75°. The angle of deviation is the angle formed by the forward extension of the incident beam and the backward extension of the emergent beam. How does the deviation vary with the angle of incidence?

Is there a minimum angle of deviation? Rotate the prism and watch the emergent beam.

Introduce a red filter. Adjust the prism for minimum deviation for red. Draw sufficient rays (as in the figure below) to find the minimum angle of deviation. Find the index of refraction, n, of the prism material, using the formula:

$$n = \frac{sin\left[\frac{1}{2}(A + \delta_{min})\right]}{sin\left[\frac{1}{2}A\right]}$$



Part XI. Dispersion

With the 60° prism set as in Part X for white light, observe the spectrum of white light. Carefully record the difference in the value for the angle of minimum deviation for red and for violet. This difference is the angle of dispersion for the prism.

Simple Harmonic Oscillator Lab

Introduction

In this lab you will study the simple harmonic motion of a mass hanging from a spring using the motion detector.

Motion Detector Reminders:

1. *To change number of graphs, go to the View – Graph Layout menu*
2. *To change type of graph click on y-axis label.*
3. *To change graph range click on number at either end of x or y axis.*
4. *Click "Collect" to collect data.*
5. *Explore the program on your own to learn more*

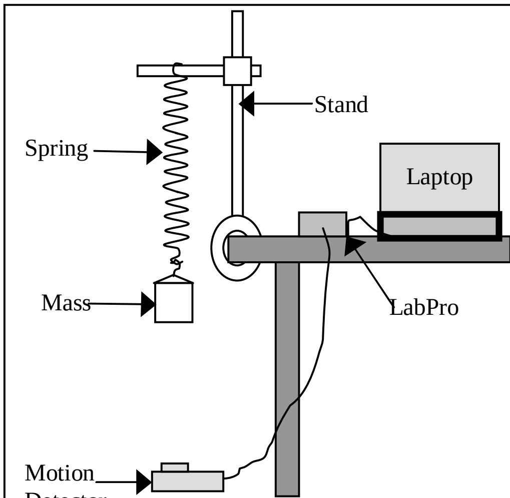


Figure 1

Figure 1 depicts the experimental setup. The mass which is attached to the spring is free to oscillate up and down. The motion detector feeds information on the mass' motion into the laptop where plots of the mass's position and velocity are made in real time.

Part A: Predictions

Before getting a spring to perform the experiments make the following predictions.

Assume the mass and spring are hooked up as shown above and the mass is pulled down and released, setting it into motion at t = 0.

1) In Figure 2 sketch your prediction for the *position vs. time (**d vs. t**)*, *velocity vs. time* (**v vs. t**) and *acceleration vs. time* (**a vs. t**) graphs for oscillation over 1 period.

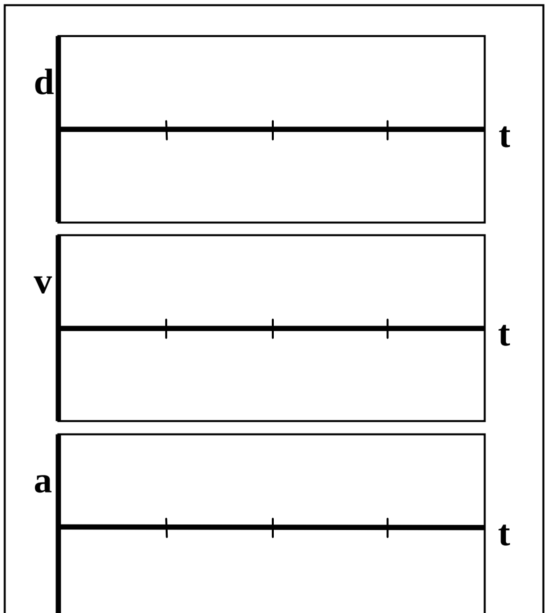


Figure 2

Part B: Equilibrium

Hang a 1.000 kg mass from the spring such that the mass is not moving. The spring will stretch by an amount $x_\circ$ (as shown in Fig 3). The force of the spring depends on the spring constant *k* and the length $x_\circ$, it is given by:

$$\mathbf{F_{spring} = -k\, x_\circ}$$

1) Assuming the mass is at rest at the bottom, draw the forces on the Free Body Diagram provided. Label each of the forces.
2) Calculate the *spring constant 'k'*. Show how you arrived at your answer.

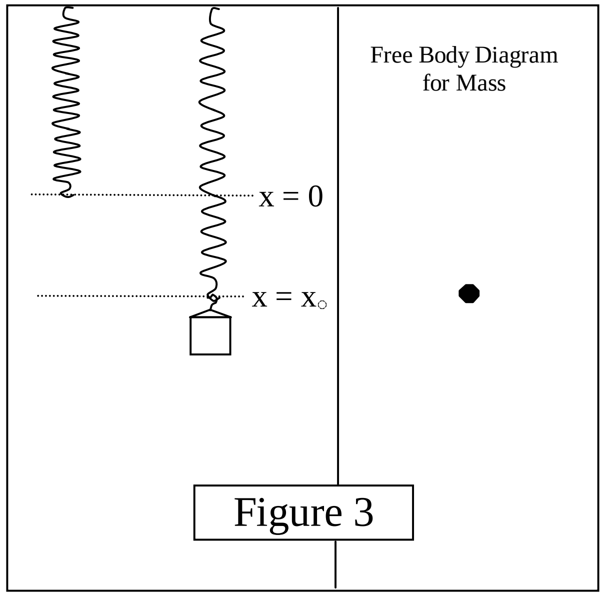


Figure 3

We will call the position of the mass when it remains at rest is the ***equilibrium position.*** *Note that the net force on the mass at equilibrium position is 0.*

Part C: Observations of Simple Harmonic Motion

First, hang 1.000 kg from the spring. Set Logger Pro to plot *position vs. time, velocity vs. time, and acceleration vs. time.* Collect a set of data with the mass at rest. *Write down the equilibrium position of the mass*. Pull the mass down a few centimeters from the equilibrium position and release it to start motion. Collect a set of data while the mass is moving.

Calculations:

1) Describe how the mass moves relative to the equilibrium position.
2) Calculate the *maximum* velocity from the *position vs. time* graph. Show your calculations. Compare with the value from the velocity time graph.
3) At what position is the velocity a *maximum*?
4) Calculate the *minimum* velocity from the *position vs. time* graph. Show your calculations. Compare with the value from the velocity time graph.
5) At what position is the velocity a *minimum*?
6) Calculate the maximum acceleration from the *velocity vs. time* graph. Show your calculations. Compare with the value from the *acceleration vs. time* graph.
7) At what position is the acceleration a *maximum?*
8) Calculate the *minimum* acceleration from the *velocity vs. time* graph. Show your calculations. Compare with the value from the *acceleration vs. time* graph
9) At what position is the acceleration a *minimum?*
10) Compare your *position*, *velocity* and *acceleration* graphs with your predictions on page 1. Resolve any discrepancies.

Part D: Investigation of the Period of Oscillation

1) **Predictions**:
   a. Predict how the Period of oscillation will change when the mass is changed. Explain your prediction.
   b. Predict how the period of oscillation will change with different initial amplitudes. Explain your prediction.
2) **Experiment**: Devise experiments to see how the *Period* depends on *Mass* and *Amplitude*. Your results must include the following graphs:
   a. Mass vs. Period
   b. Mass vs. Period^2
   c. Amplitude vs. Period
   d. Amplitude vs. Period^2
3) Compare your experimental result with your prediction. Resolve any discrepancies.

Part E: Energy conservation

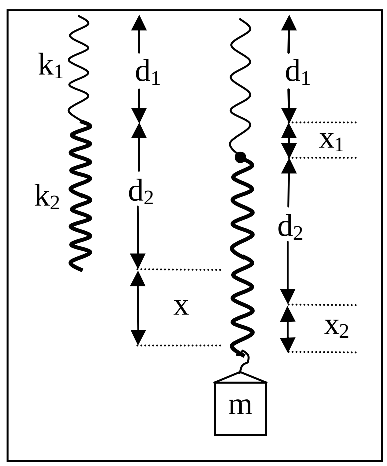
Collect a set of *position vs. time*, *velocity vs. time* and *acceleration vs. time* data for an oscillating mass of 1.000 kg.

1) **Calculation**: Test conservation of energy by calculating and comparing the total energy of the system at 2 point along the mass's path. Take the first point at to be at the highest position of the mass and the second point when the mass is at the equilibrium position.

As a mass oscillates its amplitude will very slowly decrease over time.

2) **Experiment**: Devise an experiment to determine how long it takes for the amplitude to be reduced to 2/3 of the original amplitude? Explain.
3) Does the period change as the system loses energy? Explain.
4) The reduction in amplitude represents a loss of energy by the system. Where does the energy go?

Part F: Two spring experiment



1) **Derivation**: Derive an expression for the effective spring constant (k) that results from hanging a mass from 2 springs in series as shown in the figure.
   a. Spring 1 stretches by x_1, Spring 2 by x_2 for a total stretch of x
   b. **Hint**: The 2 springs feel the same force. Use this to find x_1 in terms of x_2, k_1 and k_2.
2) **Experiment**: Devise and implement an experiment to test this result. Explain the details of your experiment.
3) Compare your experimental result with your prediction. Resolve any discrepancies.

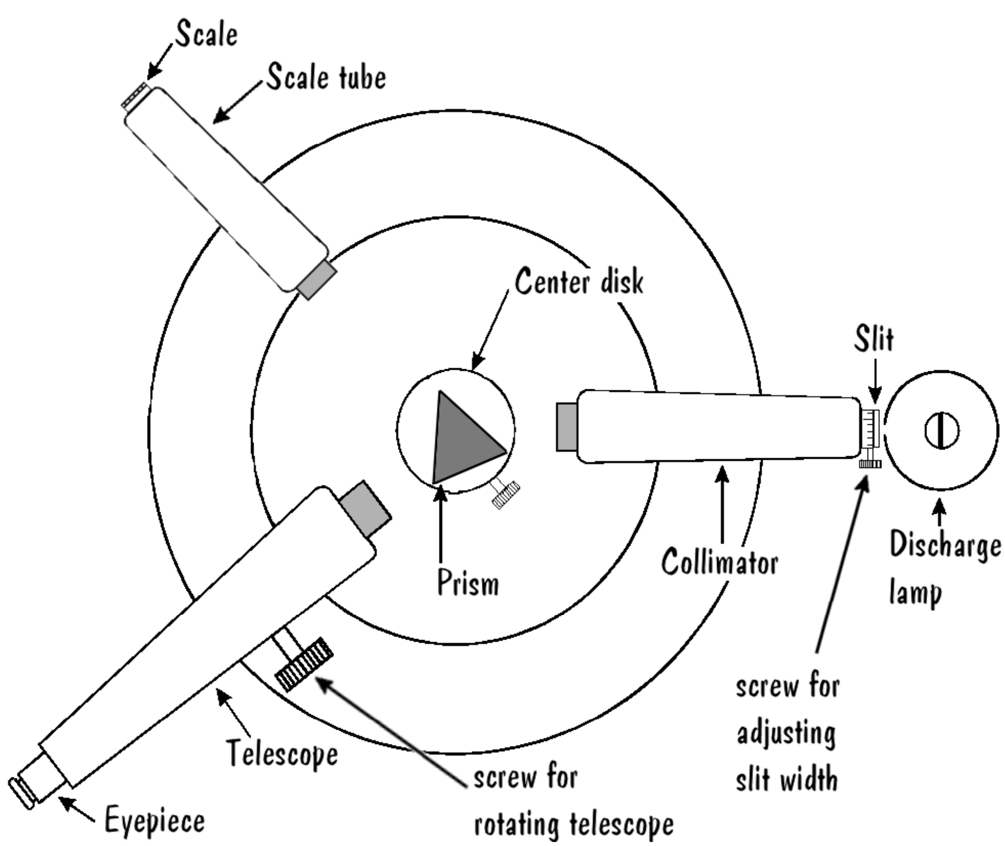
The Spectroscope

APPARATUS

1. Spectroscope
2. Mercury arc
3. Sodium Lamp
4. Geissler tubes with high voltage unit
5. Desk lamp
6. Filters

INTRODUCTION

This exercise will permit the student to study the spectroscope and to use it to examine the spectra of several light sources. The spectroscope used here consists of a collimator, a prism, a telescope, and a scale tube. The collimator is a tube having at one end a fine slit of adjustable width and at the other a converging lens. Because the slit-to-lens distance is equal to the focal length of the lens, light which diverges from the slit will become parallel upon passing through the lens. A parallel beam entering the telescope is imaged into the focal plane. The optics of the scale tube is identical with that of the collimator. The relation and function of each part is shown in the following figure.



Suppose that the collimator slit is illuminated with monochromatic light. The rays leaving the collimator are parallel and remain so through the prism though their direction is changed. (They all have the same angle of incidence and wavelength within the prism). Therefore, these rays will be brought to a focus in the focal plane of the telescope and form there a real image of the slit. If a source which contains several colors is used, several images of different color will appear, each an image of the slit formed by one constituent of the light. In order to see all these images it will be necessary to rotate the telescope by means of the knurled knob. When the outer end of the scale tube is illuminated by white light, this light is rendered parallel by the scale tube lens and reflected from the face of the prism into the telescope, so that a real image of the scale is formed in the focal plane of the telescope, coinciding with the spectrum observed. Thus the position (in arbitrary units) of the line of the spectrum can be read off directly.

PROCEDURE

Part I: The Mercury Spectrum

Place the mercury arc in front of the slit, the lamp in front of the scale tube, and look through the telescope. If necessary, slide the telescope tube in or out until the scale appears sharp. Leave the telescope tube in this position. If the slit is not in focus move the slit tube in or out until it appears sharp. If you have difficulty in making these two adjustments consult your instructor. You should see the following lines:

Color	Wavelength
Bright Violet	404.7 nm
Violet	407.8 nm
Blue	435.8 nm
Dull Green	491.6 nm
Bright Green	546.1 nm
Yellow	577.0 nm
Yellow	579.1 nm

Before you note the positions of the lines on the scale, make the slit very narrow. If you have difficulty in finding some of these lines, widen the slit, and after locating the lines make the slit narrow again. (Why?).

Part II: The Sodium Spectrum

Set up the Sodium lamp in front of the slit. If your instrument is in very good adjustment you can see two lines very close together. These lines are of wavelength 589.0 nm and 589.6 nm, but for our purposes we shall consider them as a single line of wavelength 589.3 nm. Note that the yellow line of sodium does not fall at the same position on the scale as either of the yellow mercury lines. "Yellow" is simply a region in the spectrum. Within that region may lie several lines, all of different wavelength but nevertheless all "yellow". Similar statements could he made about every spectral color.

Part III: The Helium Spectrum and the Calibration Curve

You should find the following helium lines and probably some other fainter ones:

Color	Wavelength
Blue	447.1 nm
Blue	471.3 nm
Blue green	492.2 nm
Green	504.8 nm
Yellow	587.6 nm
Red	667.8 nm
Red, faint	706.5 nm

from your results with sodium, mercury, and helium, plot a curve showing the relationship between arbitrary scale numbers as x and wavelengths in nanometers as y. This is called a "Calibration Curve" for your instrument.

Part IV: The Hydrogen Spectrum

Examine the hydrogen spectrum, record the positions of the three visible lines of the hydrogen atom. These are the red H_α, the blue-green H_β, and the violet H_γ line. The background is due to the hydrogen molecule.

Using your calibration curve from part III, determine the wavelength of each of these lines. Compare these wavelengths with those tabulated. (H_γ: 434.0 nm, H_β: 486.1 nm, H_α: 656.3 nm)

Part V: The Neon Spectrum.

Look at the spectrum of neon. Make no attempt to record the positions of all the lines. How many red lines do you observe?

Part VI: The Continuous Spectrum

Examine the spectrum of the light from a tungsten lamp. From your calibration curve, determine the range of the visible spectrum in nanometers.

Part VII: Absorption Spectra

Place each of the filters between the tungsten lamp and determine the limits (in nanometers) of each absorption band.

Part VIII: Spectral Series

In 1884 the Swiss mathematician Johann Balmer discovered that the wavelengths of the four visible lines of the Hydrogen spectrum could be represented by the formula:

$$\lambda = 364.56 \text{ nm} \, \frac{m^2}{m^2 - 4} \qquad \text{where m} \;=\; 3,\; 4,\; 5,\; \text{or } 6.$$

In 1889 Johannes Rydberg recast Balmer's formula in a new form by introducing the "wave number" $k = 1/\lambda$:

$$k = R\left(\frac{1}{4} - \frac{1}{m^2}\right), \qquad \text{where } R = 0.0109678 \text{ nm}^{-1} \text{ and n} \;=\; 3,\; 4,\; 5\; ...$$

Rydberg had shown that a similar formula applies to many series in several different elements with the same value for R. It has therefore come to be called the "Rydberg Constant". In 1913 Niels Bohr derived this formula from theoretical considerations.

Convert the measured Hydrogen wavelengths into wave numbers and calculate the value of R from each of them. Compare your mean value with the standard value.

Standing Waves in Strings

APPARATUS

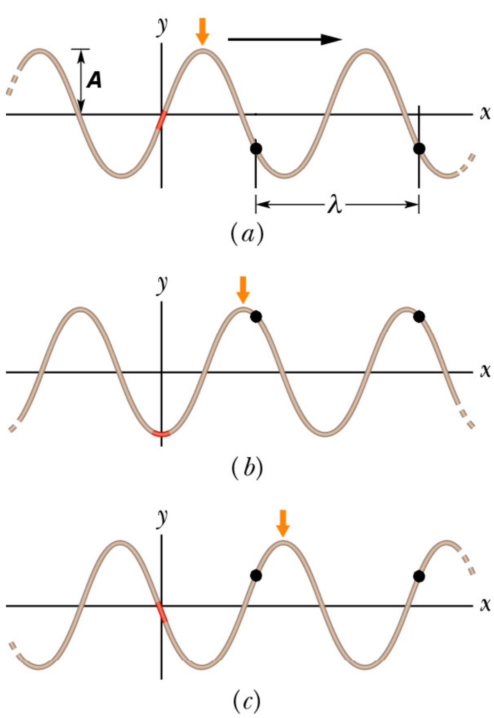
1. Buzzer (vibrating at a given frequency) mounted on a board with a pulley
2. Electronic balance
3. 2 Strings, one light and one heavy
4. Set of known masses (slotted type)
   (4 × 100 g, 4 × 50 g, 2 × 20 g, 2 × 10 g, 1 × 5 g, 2 × 2 g, 1 × 1 g)
5. A pan to support the known masses
6. Meter stick
7. 30 cm ruler

INTRODUCTION

We shall state, very briefly, some of the properties of traveling and standing waves in strings under tension which form the basis for this laboratory exercise. The student should refer to the textbook for a more complete discussion.

Traveling Waves

Consider a string along which there is a transverse traveling wave moving from left to right. In figures (1a), (1b), and (1c), we see how the string looks at slightly different times. Despite the fact that the "wave" is moving from left to right, each particular point on the string is moving up and down, and all the points on the string undergo this transverse oscillatory motion with the same amplitude. The wavelength λ (lambda) and the amplitude A of the wave are shown in Fig. (1a).



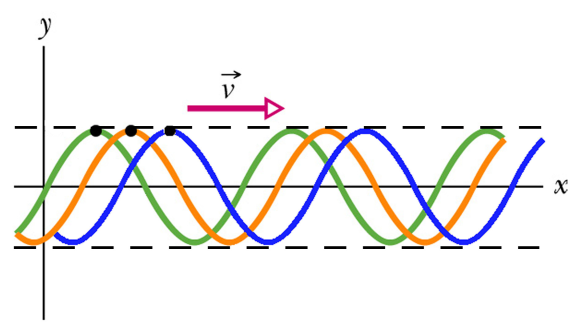


Figure 2: Traveling wave in a string at several successive times; horizontal dashed lines show the envelope of the motion.

Figure 1: A traveling wave in a string at successive times. In each picture, the black dots represent the same two points on the string while the arrow points to the propagating crest with constant phase.

Because all the points on the string are moving, the entire string would look like a blur to the eye. All that could be distinguished would be the envelope (or extremes) of the motion. This is illustrated in Fig. 2 where the solid lines represent the string at different times and the dotted lines are the envelope of the motion which indicates the outline of what the eye would see.

Standing Waves

When there are two traveling waves in the string going in opposite directions, the resultant motion of the string can be quite different than the one just described for a single traveling wave. Each wave will try to make any given point on the string undergo an oscillation of the type described above, and the actual motion of the point will be the sum of two such oscillations. Now consider the special but important case in which the two traveling waves have the same amplitude and wavelength (but are still traveling in opposite directions). We show two such waves separately in Figure 3(a) and (b).

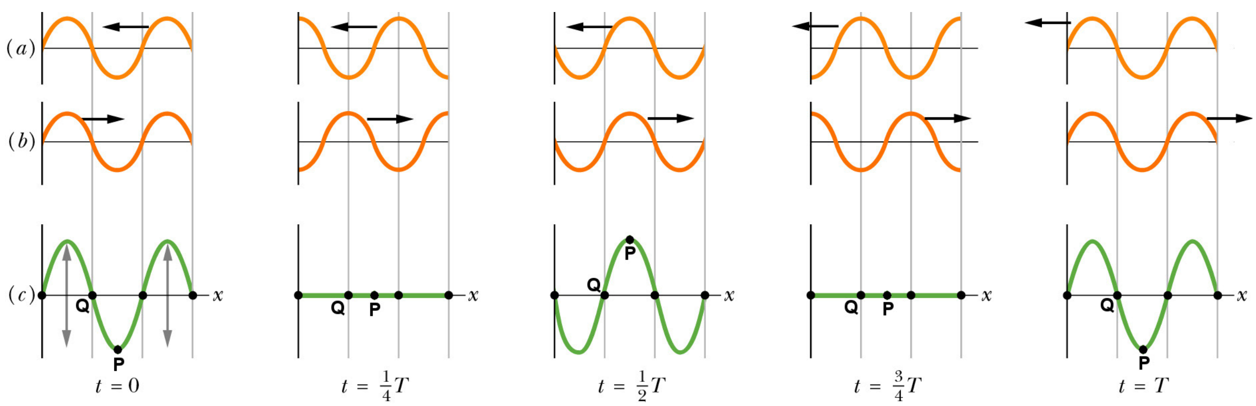


Figure 3: Two traveling waves (a) and (b) going in opposite directions generate a standing wave (c).

There is a moment (t=0 in Fig. 3) where the two counterpropagating waves are in a position to constructively interfere with each other so that the displacement of each location of the string is twice the displacement of the case of only one propagating wave. One quarter of a period later (t=$\frac{1}{4}$T in Fig. 3), the waves have moved with respect to each other for half a wavelength, causing them to destructively interfere, so that there is no displacement of any part of the string at all, momentarily. This procedure repeats itself as the waves are constantly traveling into opposite directions. Consequently, there are points (point Q in Fig. (3c)) where the string does not move at all, because at every time, the contributions from each of the waves cancel each other exactly, and there are points (point P in Fig. (3c)) which oscillate at twice the amplitude of the original waves.

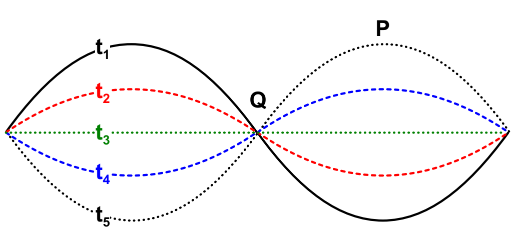


Figure 4: Appearance of a standing wave at times t = t_1, t_2, etc. Corresponding to Fig. 3: $t_3 = \frac{1}{4}$T and $t_5 = \frac{1}{2}$T

The above situation may be summarized by saying that the two traveling waves arrive at point P **in phase** and at point Q **out of phase**, and thereby produce a large oscillation at P and no motion at Q. There are many points like P and Q on the string, and other points where the waves arrive partially out of phase and produce a motion with amplitude less than that at P. At successive times t_1, t_2, etc. the string will look like the solid curves labeled t_1, t_2, etc. in Fig. 4. Points like Q which never move, because the two waves are out of phase, are called **nodes**, and points like P which have large amplitude of transverse motion because the two waves are in phase are called **antinodes**. The distance between two adjacent nodes is equal to one half wavelength of the traveling waves.

The motion pictured in Fig. 4 is an example of a standing wave, and it looks quite different to the observer than the traveling wave of Fig. 2. It is easy to see the nodes in standing waves, and thereby make a direct determination of the wavelength. When a string is held fixed at two particular points, then any standing waves which exist in the string will have nodes at those two fixed points. Thus, if the fixed points are Q and Q' in Figure 5, then the standing waves shown in (5a), (5b), (5c) are all possible because they each have nodes at Q and Q'. The waves in figures (5a), (5b), and (5c) are examples of standing wave patterns (also called "modes of oscillation") for a string fixed at Q and Q'.

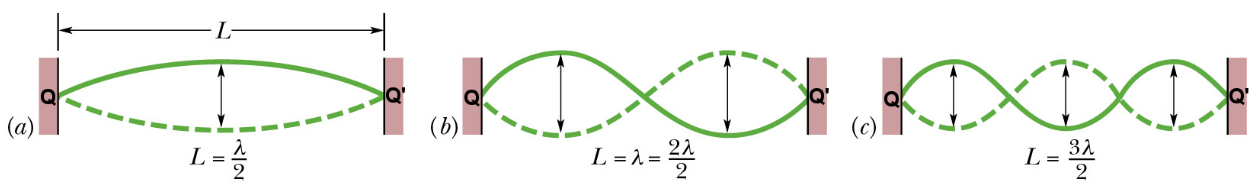


Figure 5: Three possibilities of standing waves (modes of oscillation) on a string of fixed length L.

For waves in strings the wavelength λ is related to the frequency f and velocity v by:

$$v = f\lambda \tag{1}$$

The velocity of a transverse wave in a string is given by

$$v = \sqrt{\frac{F}{\mu}} \tag{2}$$

where F is the tension in the string and μ is the mass per unit length of the string. Equating equations (1) and (2), one gets:

$$f = \frac{1}{\lambda}\sqrt{\frac{F}{\mu}} \tag{3}$$

In the setup used in this experiment, the tension is generated by a mass that pulls on the string over a pulley, the tension in the string is therefore $F = mg$ with g=9.806 m/s^2. By varying this tension, the sound velocity (and thus, the wavelength corresponding to a fixed frequency) will be so altered that several standing wave patterns can be found. That is, over the string's entire length there will be two, three, or more nodes.

Determination of the Frequency of a Source Using a Standing Wave.

Standing waves are to be set up in a stretched string by the vibrations of a buzzer driven by an alternating current. The frequency of vibration is 120 Hertz.

You are supposed to vary the tension in the string, by varying the mass m (masses of the pan and the slotted masses) suspended over the pulley, until resonance is reached. Then, record the value of the suspended mass, and the distance L, between nodes of the standing wave. In each case the wavelength is equal to twice the distance between neighboring nodes, i. e. $\lambda = 2L$. Make sure that the nodes are as sharp and distinct as possible. The sound of the vibrator will indicate to some extent when resonance is reached and the amplitude will reach a maximum value. Also, at resonance, adding or removing 5 grams should reduce the amplitude of the standing wave.

PROCEDURE

1. Using one of the strings determine the tension in the string and the wavelength for as many different standing wave patterns (at least four) as possible. It is suggested to start with the light string.
2. From these data plot two curves on the same sheet:
   (a) Plot tension on the X axis and wavelength on the y axis.
   (b) Plot tension on the X axis and (wavelength)^2 on the y axis.
3. Determine the mass per unit length of the string. Then calculate the average frequency. Do this by first determining the slope of the second of the above graphs and then interpret its significance with the aid of equation (3).
4. Repeat 1-3 using the other string.
5. In each case, assume f=120 Hz to be the correct value of the frequency and determine the percentage error in the calculated frequency:

$$\frac{f_{measured} - f}{f} \times 100\%$$

Questions (to be answered in your report):

1. Did you observe longitudinal or transverse waves in this experiment?
2. In any two cases above, calculate the velocity of the wave in the string.
3. What is the shape of each curve plotted?
4. Does each curve agree with equation (3)?
5. When there are three or more loops, why is it better to use one of the inner loops to measure L, rather than one of the loops formed at either end of the string?

Vectors - Equilibrium of a Particle

APPARATUS

1. A force table equipped with a ring, pin, four pulleys, cords and pans
2. A set of 16 slotted masses: Set of known masses (slotted type)
   (4 × 100 g, 4 × 50 g, 2 × 20 g, 2 × 10 g, 1 × 5 g, 2 × 2 g, 1 × 1 g)
3. Protractor
4. Ruler

INTRODUCTION

Physical quantities that require both a magnitude and direction for their description are vector quantities. Vectors must be added by special rules that take both parts of the description into account. One method for adding vectors is graphical, constructing a diagram in which the vectors are represented by arrows drawn to scale and oriented with respect to a fixed direction.

Using the graphic method we can rapidly solve problems involving the equilibrium of a particle, in which the vector sum of the forces acting on the particle must be equal to zero. While the graphical method has lower accuracy than analytical methods, it is a way of getting a feel for the relative magnitude and direction of the forces. It can also solve the problem of the ambiguity of the direction of a force where the analytical method uses an arctangent to determine direction, which gives angles in the range $-90°$ to $+90°$.

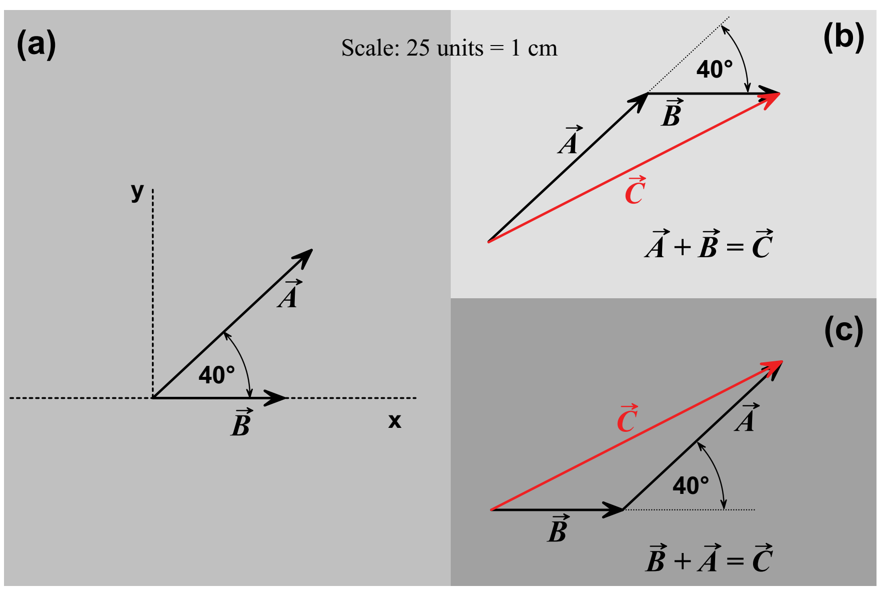


Figure 1: Graphical addition of two vectors

The graphical addition of two vectors is illustrated in Figure 1. A suitable scale must be chosen, so that the diagram will be large enough to fill most of the work space. The scale is written in the work space in the form of an equation, as appears at the top of Figure 1. This is read as ”25 units of force are represented by 1 cm on the page”.

A 0° direction should also be indicated, for example the x axis in Figure 1(a). Figure 1(b) illustrates starting with $\vec{A}$, while Figure 1(c) starts with $\vec{B}$. In each case the second vector is drawn from the head of the first vector (this is the head-to-tail rule). Note that the direction of the second vector is measured from the direction of the first vector as shown in Figure 1(c).

Note also that the vectors are labeled as they are completed.

You can think of this process as "walking" along segments of a path. The equivalent walk, or **resultant vector**, goes from the beginning (tail) of the first vector to the head of the last vector. This is the vector $\vec{C}$ shown in Figures 1(b) and 1(c). The length of this vector can be measured and the scale used to convert back to force units. The direction can also be measured, so that the force vector is then completely described.

In the addition of more than two vectors the procedure is the same, as shown in Figure 2. Vectors are drawn head-to-tail. Shown is $\vec{B} + \vec{A} + \vec{D} = \vec{E}$.

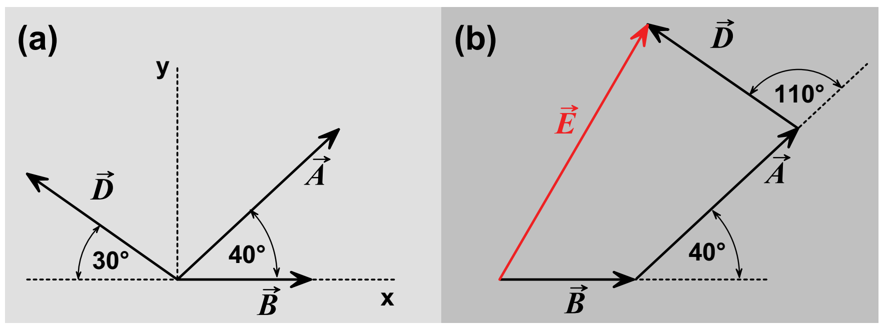


Figure 2: Graphical addition of three vectors

NOTES AND TECHNIQUES

1. We will use "grams" as a unit of force. While not strictly correct, the weight of a given mass is proportional to that mass.

2. The central ring has spokes that connect the inner and outer edges. When connecting the cords be sure that the hooks have not snagged on a spoke. In that case the cord will not be radial. Also whenever you change a pulley position, check that the cord is still radial.

3. Be sure that when you position a pulley, that both edges of the clamp arc snugly against the edge of the force table. Check that the cord is on the pulley.

4. There are two tests for equilibrium.
   The first test is to move the pin up and down and observe the ring. If it moves with the pin, the system is NOT in equilibrium and forces need to be adjusted.
   The second test is to remove the pin. However, this should be done in two stages. First just lift it but hold it in the ring to prevent large motions. If there is no motion, remove it completely. If the ring remains centered then the system is in equilibrium.

5. The circle diagram is a quick sketch of the top of the table and summarizes the forces acting on the ring (the particle). Do not spend time making this "pretty". The vector addition diagrams are to be done carefully with ruler and protractor.

PROCEDURE

Part I: Resultant and Equilibrant of Two Forces

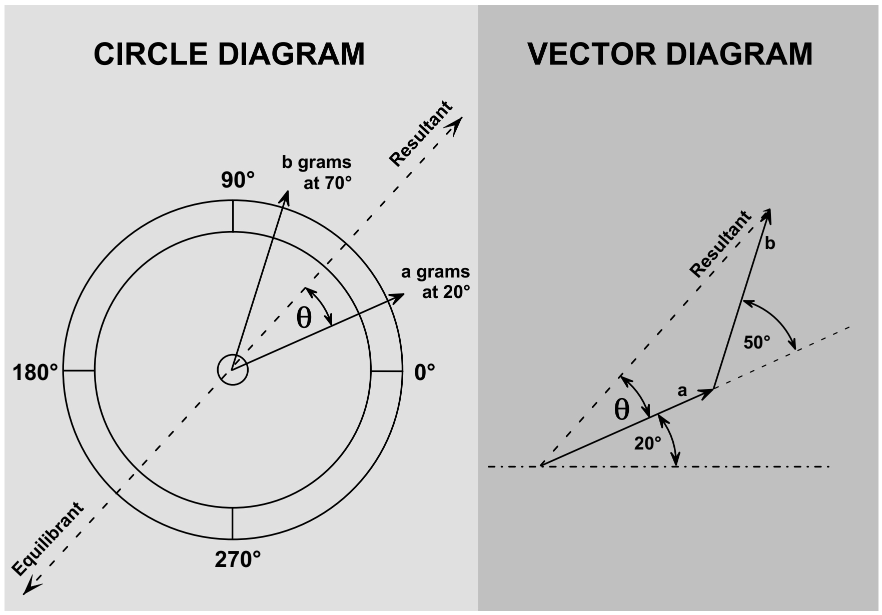


Figure 3

(a) Mount one pulley on the force table at the 0° mark. Mount a second pulley at any angle between 50° and 80°. Suspend unequal loads on cords running from the central disk over the pulleys. Record the angles and the loads on a circle diagram. Remember that the pans weigh 50 grams.

(b) Choose a scale so that the sum of the two forces would almost reach across the page. Draw a scale diagram of the two vectors in the "head to tail" position, as in the $\vec{A} - \vec{B}$ portion of Figures 1(c) or 2(b). Complete the diagram so as to determine the magnitude and direction of the resultant, as in Figure 1(c). The resultant is the single force that is the sum of the two original forces.
Write down the size of the resultant and its direction.

(c) The equilibrant is the single force that would balance the original two forces. It should be equal in size to the resultant, and opposite in direction. Mount a pulley at this angle on the force table, and use a cord to apply the appropriate load. Perform the first test for equilibrium (moving the pin).
You may have to vary the load slightly, or the angle to obtain a good balance. When you think this has been achieved, perform the second test (removing the pin). Record the final values of the load and angle.

Questions (to be answered in your report): How close did the final values come to the values determined from the vector addition diagram? (You should have been able to get within 3 grams and 1.5 degrees.)

Part II: Addition of Four Forces Producing Equilibrium

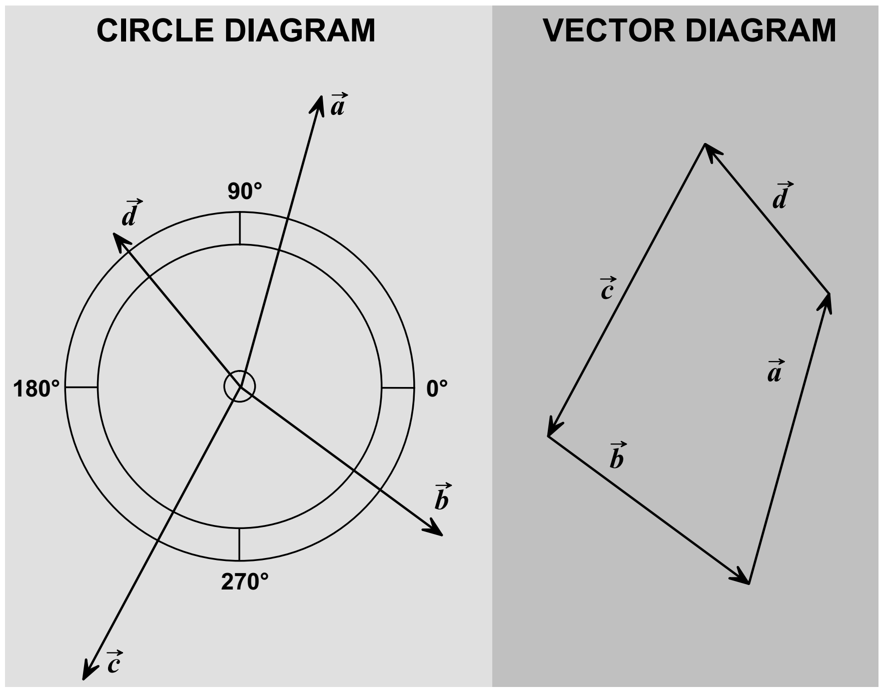


Figure 4

(a) Set up four pulleys and suspend unequal loads on the cords running over them. Change angles and loads until the system is in equilibrium (i.e. passes both tests). Be sure that the cords are still radial. Sketch the circle diagram to record loads (remember the weight of the pans) and angles.

(b) Carefully draw the vector addition diagram (see figure 4). Note that your diagram may not close due to small errors.

Questions (to be answered in your report):

1. How large is the resultant of the four force vectors in your diagram?
2. Why should we expect the vector addition diagram to close?

(c) The discrepancy can arise from two sources, errors in the lengths of the lines in our diagram and errors in angles. We can estimate the uncertainty in each by noting the sensitivity of the ruler (ΔL) and protractor ($\Delta\theta$). (Sensitivity is the smallest quantity that can be read or estimated from a scale.) Convert ΔL to a force by using your scale value. Convert $\Delta\theta$ to radians and multiply by twice the largest force in the diagram. ($180° = \pi$ Rad.) The sum of these two terms is an estimate of the uncertainty in the resultant.

Questions (to be answered in your report): How does the size of your resultant in (b) compare with this uncertainty?

Part III: Determination of X and Y Components of a Force

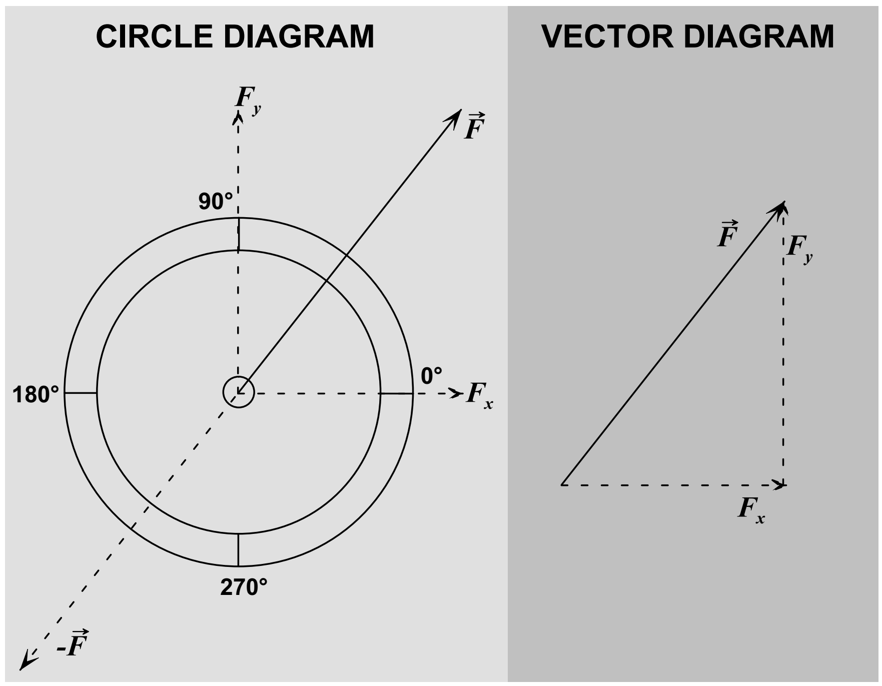


Figure 5

(a) Place a pulley on the 30° mark of the force table and apply a load over it. Note the total load and angle at the top of a data sheet.

(b) If the resultant of the vector sum of two forces is the single force that is an exact equivalent of the two original forces, then we can reverse the process and find the two forces, in convenient directions, that is equivalent to any given single force.
Draw a set of X-Y axes at the lower left of your data sheet. Choose a scale so that the vector representing your load will span most of the page. Draw the vector representing your load, assuming that the positive X axis is the 0° direction.
Drop a perpendicular to the X axis from the head of your vector (this line makes an angle of 60° with the direction of the vector).
Draw arrow heads on the two legs of the resulting right triangle, as if they were two vectors that added to the vector on the hypotenuse.

(c) The vector along the X axis and the vector parallel to the Y axis are called component vectors[1]. Convert to force values and sketch a circle diagram with the results.
Set up these forces on your force table. Move the original load by 180°, to 210°.
Test for equilibrium, and make any necessary adjustments to the load to balance.

Questions (to be answered in your report): : How large an adjustment did you have to make? How does this compare with the uncertainty you found in II.(c)?

(d) The sides of the right triangle can also be determined by trigonometry. Calculate the size of the component vectors trigonometrically. Show your calculation. How do they compare with the values you found graphically ?

[1]Components are scalars that have an accompanying indication of direction.