

Doth God exact day-labor, light denied?
 John Milton, *On His Blindness*, 1652.

Introduction

You will continue your exploration into geometrical optics by observing and quantifying the effects of lens shape and material on the path of three parallel incident rays. You will begin by passing light through a water-filled, hollow lens surrounded by air. Then you will replace the water with air and vice versa, and you will observe what happens to light that passes through an air lens surrounded by water. You will compare the focusing properties of cylindrical lenses and spherical lenses in the context of human vision with an emphasis on an astigmatic eye. You will explore image formation by thin lenses and spherical mirrors, and you will learn about measuring focal length in diopters. You will also learn about nearsightedness and farsightedness.

Procedure

In the first part of today’s lab, you will use a hollow cylindrical lens (curvature about only one axis) to observe the effects of differently shaped lenses on the path of three parallel light rays. The hollow lens is a small acrylic container that that you can turn into different lenses simply by adding water to individual compartments. Figure 1 shows a **top view** of the container; it shows four possible ways that you can make a lens by adding water. A spot indicates the center of each lens.

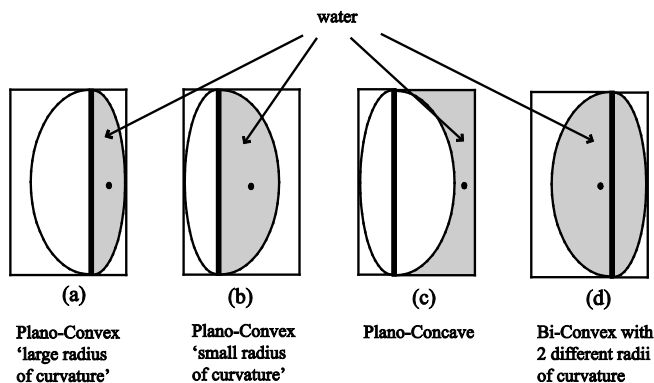


Figure 1

Figure 2 shows the setup for this part of the lab. The light box is set to emit three parallel light rays.

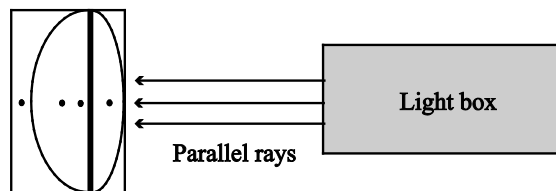


Figure 2

Exercise 1 Converging and Diverging Lenses

Use a plastic pipette to fill the hollow lens as shown in Figure 1a, and then align the lens so that the middle ray from the light box passes through the center of the lens. (You might want to set the lens on a small piece of foam board equal in size to the base of the lens.) Adjust the position of the lens until all three rays focus to a thin line before diverging again. **Note: You will see several other light rays that are due to reflections. If you are unsure of the three that we are interested in, ask your instructor for clarification.**

Q1: Describe what happens to the three rays after they pass through the lens. (This lens is a 'converging' lens.)

Roughly Measure the distance between the center of the lens and the point where all three rays intersect.

Slide the lens along the table so that the three parallel rays strike the lens 'off axis' as shown in Figure 3. (You should also try this with five parallel rays.)

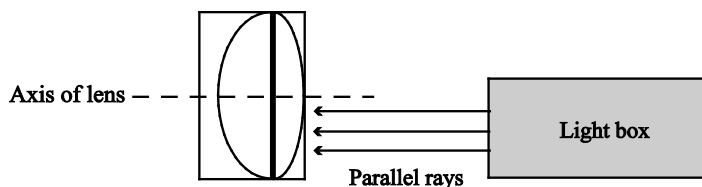


Figure 3

Q2: Explain why/how the rays still converge to a point on the axis. (A simple drawing might help.)

Empty the water from the lens and make the lens shown in Figure 1b.

Measure the distance between the center of the lens and the point where the three rays intersect.

The Radius of Curvature

The curved surfaces of the cylindrical lens you've been using may or may not be exactly circular - it's difficult to tell. Even if they aren't circular, there is a circle of radius R that has the same curvature along the axis as the lens. Figure 4 is a top view of two curved surfaces and the circles that define their radii. In general, the more curvature there is to a surface, the smaller the radius of curvature. **Note: The radius of curvature of a planar surface is infinite.**

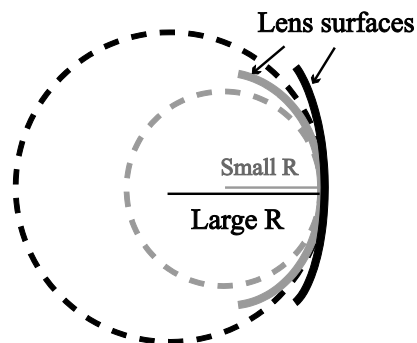


Figure 4

Q3: What effect does the radius of curvature have on the distance from the center of the lens to the point where the rays converge?

Add water so that you will have the lens shown in Figure 1d.

Q4: What effect does this change have on the distance from the center of the lens to the point where the rays converge?

Q5: Does it matter which surface is nearer to the light source? (We will come back to this when we introduce the lensmaker's formula.)

Pour out the water, and then fill the compartment shown in Figure 1c.

Q6: What happens to the rays after they pass through the lens? (This lens is a 'diverging' lens.)

Exercise 2 The 'Air Lens'

We are now going to reverse the mediums of Exercise 1. In this exercise, the lens will be made of air, and the medium surrounding it will be water.

Before you do anything here, think about what will happen and make the following predictions ([the definitions of convex and concave are found in Figure 1](#)):

Would a double convex air lens immersed in water be a converging lens or a diverging lens?

How about a double concave air lens?

Add water to a rectangular acrylic container until it's about $\frac{3}{4}$ full. Place the hollow lens in the water, keeping the lens filled as shown in Figure 1c. Figure 5 is a top view of the lens in water. This creates a lens similar to the lens in Figure 1d, but with the air and water reversed; it is an "air lens".

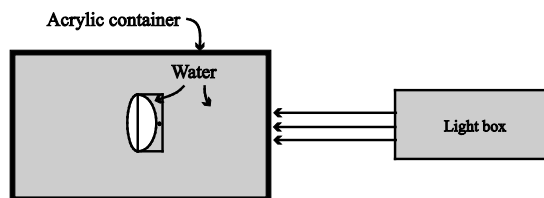


Figure 5

The lens will tend to float because of the buoyant force, so you will have to hold it down. Shine the parallel light rays through the lens and **record your observations**. (If you're not sure which rays to look at, ask your instructor.)

Empty the lens and then fill with water all the compartments except for the one shown in Figure 1c. Place the lens back into the water and shine the light through it. **Record your observations**.

Q7: Explain using simple diagrams what is happening here. Were your predictions correct?

Exercise 3 Spherical vs. Cylindrical Lenses - Astigmatism

Some of the lenses you will use later in this lab are spherical lenses, not cylindrical lenses. That is, the shapes that define the radii shown in Figure 4 are now spherical. (This means that each surface is defined by the surface of a sphere rather than a cylinder.) The difference in shape has an important consequence in terms of focusing ability. For example, some people have eyes that need spectacles with only spherical correcting lenses, and others have *astigmatism* that needs a cylindrical lens. (Your instructor will show you an eye chart that is used to test for astigmatism.)

Hold a bi-convex spherical (plastic, not water!) lens about 1 cm above the words on this page and **observe what happens, if anything, to the image as you rotate the lens**. (Rotate the lens about a line **perpendicular** to the surface of the lens.) ~~Be sure to discuss your results with your instructor.~~ Record your observations.

Fill the compartment of the hollow lens in Figure 1b about half full. Hold the lens at eye level and hold this page (or another one) behind it so that as you look through the lens you see a focused, enlarged image of the words. **Observe what happens to the image as you rotate the lens**. (As soon as the water begins to spill from the lens, you'll know you've gone too far. Perhaps you'll decide to rotate the page rather than the lens. Also, your instructor might show you a cylindrical plastic ruler that you can use instead of the water-filled lens.) ~~Be sure to discuss your results with your instructor.~~ Record your observations.

~~Record your observations~~ and Briefly explain why nothing happened when you rotated the spherical lens whereas when you rotated the cylindrical lens, the appearance of the image changed.

In an astigmatic eye, the cornea is curved more about one axis than another, turning it into a lens with cylindrical characteristics in addition to spherical properties.

There are a few cylindrical ‘correction lenses’ in the lab. Have your lab partner hold up a paper while you look through a lens to make an ‘astigmatic eye.’ Bring a correction lens in front of the astigmatic eye and find the orientation of the lens that corrects for the distortion. (Your instructor might show you an eye model that you can use to demonstrate astigmatism.)

Q8: *What is the relationship between the long axis of the astigmatic eye and the long axis of the correction lens? (The ‘long axis’ refers to the axis of the cylinder of which these small pieces are a part. In order to answer this question, you will need to pay attention to whether the lenses are both concave, both convex, or one of each.)*

The Focal Length

In your observations so far, you should have noticed that the three parallel rays from the light box all converge to one point (or thin line) after passing through the lens and then they continue to diverge after that. By definition, the point where the three initially **parallel rays** converge is called the focal point, F , of the lens. The distance between the center of the lens and the focal point is called the *focal length*, f . Figure 6 shows the refraction that occurs at each surface (R_1 and R_2) of the lens for the upper and lower rays and for the unrefracted ray that travels along the optical axis. The intersection of these three rays defines the focal length of the lens. (By default, it is the focal length of the lens in air.)

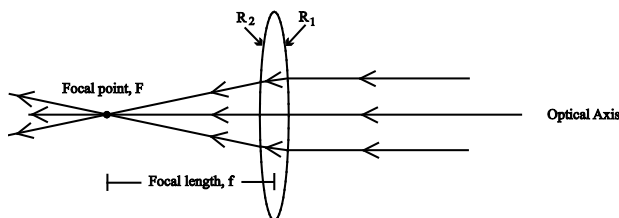


Figure 6

Sign Conventions

When you do calculations involving lenses, you must be aware of sign conventions that dictate when a value is -positive and when it is -negative. **By definition, if the image focuses on the opposite side of the lens from the object, the focal length is positive. If the image focuses on the same side of the lens as the object, the focal length is negative.**

For the lensmaker’s formula that follows, we also need to know the sign convention for the radii of curvature of the two lens surfaces. In Figure 6, each surface has the same magnitude for its radius of curvature; this is not always the case. The sign convention is as follows:

The radius is positive if the surface is convex toward the object and negative if the surface is concave toward the object. In Figure 6 then, R_1 is positive and R_2 is negative.

* In Figure 6, the object is to the right of the lens.

The Lensmaker's Equation Formula

The lensmaker's Equation formula is most often written with the assumption that the lens is surrounded by air (good assumption for eyeglasses!), and is

$$\frac{1}{f} = (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right), \quad (1)$$

where the '1' in (n-1) represents the index of refraction of air.

A more general expression is

$$\frac{1}{f} = \frac{n_{lens} - n_{medium}}{n_{medium}} \left(\frac{1}{R_1} - \frac{1}{R_2} \right),$$

$$\frac{1}{f} = (n_{lens} - n_{medium}) \left(\frac{1}{R_1} - \frac{1}{R_2} \right), \quad (2)$$

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where n_{lens} is the index refraction of the lens material and n_{medium} is the index of refraction of the medium surrounding the lens.

In Exercise 1, you should have found that the focal length of the lens in Figure 1d did not depend on which surface was closest to the light box. Equation (1) shows why. [Suppose you change the lens surface that's closest to the light box. What happens to R_1 and R_2 ? What happens to equation (1)?]

Exercise 4

Here is a simple exercise to illustrate the difference in the focal length of a glass lens in air compared to its focal length in water. Hold a plastic biconvex lens upright on the tabletop and shine the three light rays through it. Use a piece of foam board to find the focused image. **Measure the focal length of the lens in air.**

Place the lens in a rectangular container $\frac{3}{4}$ full of water as shown in Figure 7. Use a piece of plastic to find the focused image and measure the focal length of the lens in water.

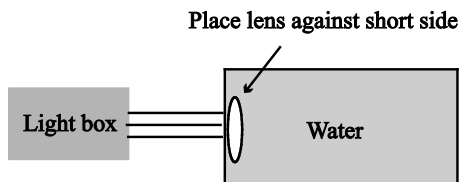


Figure 7

Calculate the ratio of the focal length in water to the focal length in air.

Use the lensmaker's formula to **calculate a theoretical value for the ratio of the focal length in water to the focal length in air**. Use 1.49 for the index of refraction of plastic. (**HINT**: You will not need values for R_1 and R_2 .)

The theoretical value should be close to the experimental value. If it is not, recheck your data.

Q9: *What values did you get for the ratio?*

The Thin Lens Equation

You have already observed the effects of passing **parallel rays** of light through a converging lens and through a diverging lens. Parallel rays can be produced in several ways. They can be produced as in the case of the light box. They can be produced by an object that is very from the lens. And they can be produced by a lens.

In many cases, light rays are not parallel when they encounter a lens; Figure 8 shows this situation. Light is emitted or reflected from one object in many directions. Fortunately for us, we need only two rays to predict where the image will focus and what the properties of the image will be. Here we have chosen to follow the path of three rays (one more than needed). The rays were reflected from the arrow, and Figure 8 shows their paths.

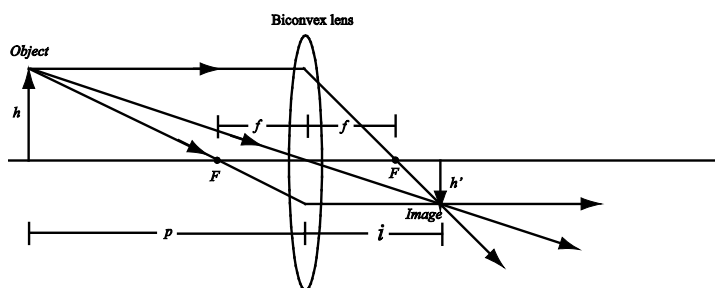


Figure 8

A simple equation governs where the image of the arrow will form. The **thin lens equation** is

$$\frac{1}{f} = \frac{1}{o} + \frac{1}{i}, \quad (3)$$

where f is the focal length of the lens, o is the object distance, and i is the image distance as shown in Figure 8 (please re-label the ' p ' in Figure 8 with an ' o ').[†] Since a lens has two surfaces, refraction occurs at both surfaces. However, for simplicity we have drawn refraction only at the center of the lens. (This is related to the thin lens approximation.)

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[†] Sometimes the lensmaker's equation is called "the thin lens equation". See, e.g., *Physics: Calculus, 2nd ed.*, by Eugene Hecht, p. 954.

. He's not correct. The Lens maker's equation has only to do with the characteristics of the lens, not with the object and image distance. I confirmed this with Ted.

These rules govern ray diagrams for a thin lens:

- Rays parallel to the axis refract and pass through the focal point on the opposite side of the lens.
- Rays that pass through the focal point on the same side of the lens as the object refract and then leave the lens parallel to the axis.
- Rays that pass through the center of the lens are not refracted.

Note that distances are measured to the center of the lens. For a converging lens, the focal length f is taken to be a positive quantity. In the situation shown in Figure 8, where the image appears on the opposite side of the lens from the object, the object and image distances, o and i , are also positive.

Another important quantity that characterizes the image formed by the lens is the *magnification* of the system.[‡] The magnification, M , is defined as the ratio of the transverse dimension of the image to that of the object,

$$M \equiv \frac{h'}{h}, \quad (4a)$$

where h' is negative because the image is upside down. It is easy to show from the ray diagram above and simple geometry that

$$M = -\frac{i}{o}. \quad (4b)$$

The negative sign in equation (4b) denotes that the image is inverted.

Figure 9 shows the ray diagram for a diverging lens.

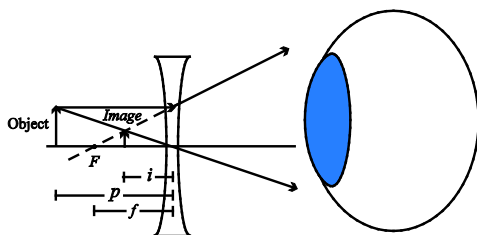


Figure 9

The rays passing through the lens diverge on the far side and therefore never form a real image. (In other words, the rays to the right of the lens in Figure 9 never meet.) Instead, the rays are projected "back" by your eye (and your brain) to form a virtual image. This means that the image from a

[‡] The magnification described here is *lateral* or *transverse* magnification, which is somewhat different from *angular* magnification.

diverging lens cannot be focused to a point on a distant screen. The lens equation is still valid, but for a diverging lens, the **image distance is negative** since the image forms on the same side of the lens as the object. Note that the image in Figure 9 is upright, 'minified,' and virtual. (Minification is the opposite of magnification.)

Exercise 5 The Thin Converging Lens

You will now use an optical bench and a thin lens to explore image formation. In your box of lenses, you will find three converging lenses (lenses 1-3) and one diverging lens (lens 4). For this part of the lab, you will use lens 2. Place the light source at the zero mark on the bench, and place the screen at the 100 cm mark. Place lens 2 in a lens holder between the light source and the screen. (If you need help with the lens holder, consult your instructor.) **Check with your instructor to be sure that you are using lens 2.** (Sometimes the lenses are put in the wrong slots in the box.)

If the distance between the object and the screen remains fixed ($o + i$ is a constant) and the lens is moved along the bench, then the lens equation implies that there will be **two** lens positions that lead to a sharp image forming on the screen.

Find both of these positions and use each one to **calculate the focal length of the lens using equation (3).**

Q10: *What value did you get for the focal length?*

Using the lens position where the image is the largest, **calculate the magnification two different ways, once using equation (4a) and once using equation (4b).**

Q11: *What values did you get for the magnification?*

Here's a test of your intuition. (Think about your answer *before* you try this experimentally!)

Suppose you have a nice sharp image on the screen and you block half the **lens** with an opaque piece of paper.

What do you think will happen to the image?

Q12: Test your hypothesis and *explain what happens*. Discuss your results with your instructor.

Exercise 6 The Thin Diverging Lens

Hold the diverging lens (lens 4 in the box) slightly above the words on this page and carefully observe where the image forms. The ray diagram for the diverging lens in Figure 9 indicates that the image will form on the same side of the lens as the object. If your eye is to the right of the lens in Figure 9, this means you should observe that the image appears lifted off the page. See whether you observe this.

There is no way for you to directly measure the image distance of a diverging lens. Therefore, you cannot find its focal length in the same manner as for a converging lens. However, if you place a diverging lens and a converging lens in contact with one another, you can determine an equivalent

focal length by measuring the image and object distances and applying equation (3). (In other words, you can find the focal length for the **combination** of lenses.) Using the following equation, you can then calculate the focal length of the diverging lens.

$$\frac{1}{f_{equiv}} = \frac{1}{f_{conv}} + \frac{1}{f_{div}} \quad (5)$$

(In equation (5), f_{equiv} is the focal length of the combined lenses, f_{conv} is the focal length of the converging lens, and f_{div} is the focal length of the diverging lens.)

Place the diverging lens (lens 4) and lens 2 together in the same lens holder. (This is not easy. If you need help, consult our instructor.) Focus the image from the combined lenses onto the screen.

Do a simple test to see if the order of the lenses matters.

Focus an image on the screen and measure o and i . Calculate the equivalent focal length of the combined lenses. Use this value to calculate the focal length of the diverging lens using equation (5).

Q13: What value did you get for the focal length of the diverging lens?

I will probably not have my groups do this part.

Exercise 7 Measuring Focal Length in Diopters

Look at equation (5). All of the terms in that equation are the inverses of focal lengths. This helps explain why optometrists, ophthalmologists, and opticians specify the *dioptric power* (or just “the power”) of a lens rather than its focal length.[§] The dioptric power of a lens is simply the reciprocal of the focal length. Power has the units of inverse meters, or diopters (D), $1 \text{ m}^{-1} = 1 \text{ D}$.^{**} In order to calculate the power of a lens in diopters, you must take the **inverse of the focal length measured in meters**. Using D for dioptric power, equation (5) becomes

$$D_{equiv} = D_{conv} + D_{div} \quad (6)$$

Q14: What is the power (in diopters) of a lens whose focal length is .4 meters?

Q15: Suppose you place in one lens holder a converging lens and a diverging lens. If the converging lens has a power of 4 D and the diverging lens has a power of -2 D, what will be the power (in D) of the combination? What will be the focal length of the combination?

[§] Dioptric power is sometimes referred to as “corrective power” or “refractive power”. (See *Physics for Scientists and Engineers*, 3rd ed., by Wolfson and Pasachoff.; and *Physics*, 8th ed., by Cutnell and Johnson.)

^{**} This definition is from *Physics: Calculus*, 2nd ed., by Eugene Hecht, p. 970.

I probably won't do the lensometer part.

Exercise 8 Myopia, Hyperopia, Presbyopia, Astigmatism, and the Lensometer

You will work with two types of eye models (what is the second type?, and your instructor will explain myopia, hyperopia, and presbyopia. Your instructor will also explain more about astigmatism, show you a lensometer (also called a phacometer), and explain eyeglass prescriptions.

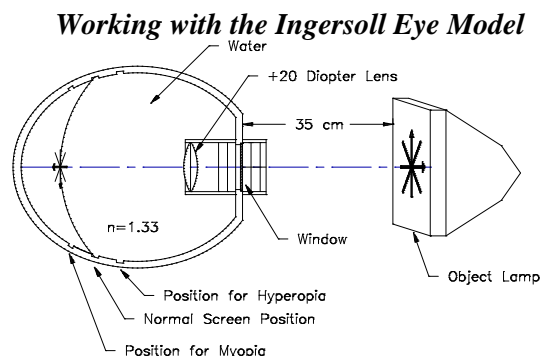


Figure 10 Diagram showing how to setup the Ingersoll eye model.

Figure 10 is a diagram of the Ingersoll eye model. The model is first filled with distilled water to within about 2 cm. of the top. The water simulates the *vitreous humor* of the eye. A small black box contains the lenses to be used with the eye model. Find the +20 diopter lens and place it in the slot **in the water and closest to the simulated retina**. (The simulated retina is the curved, removable metal plate.) This lens simulates the *crystalline lens*. Place the simulated retina at the center (normal) position. The illuminated object should be set about a third of a meter away from the model. Adjust the position of the **object** until you see a **clear** image on the screen representing the retina. This represents a normal eye. Now, move the screen in the eye model to the position farthest from the crystalline lens. Observe and record the appearance of the image. This represents myopia (nearsightedness); the image is now formed in front of the retina. You can correct this condition by placing a lens in front of the eye (outside the water!). Try the +2.00D and the -1.75D lenses. (The model is now wearing glasses!)

Q16: Which lens works? Is it a converging or diverging lens?

Repeat the procedure with the screen in the near position (representing hyperopia).

Q17: Which lens corrects hyperopia (farsightedness)?

Return the “retina” is to the center (normal) position. Place an illuminated object about 35 cm from the eye model, and adjust the object position until a clear image is obtained on the retina. Now, insert a -5.5D **cylindrical** lens in the lens support nearest the “cornea” **in the water**. The *axis* of the cylindrical lens is marked by two small lines on the lens. Be sure that the axis is vertical. (You are causing the model to have *astigmatism*.) What happens to the image on the retina? Now, insert a +1.75D **cylindrical** lens in front of the “cornea” (outside the water!). Rotate the +1.75D lens, and see what happens; get the best image that you can. Now, rotate the -5.5D cylindrical lens, which is in

the water. Again rotate the +1.75D lens to get the best image that you can. Try to explain what's going on. If you need help explaining this, consult your instructor.

Q18: *Assume that a nearsighted student has eyeglasses with lenses that are perfectly round. (i.e., Each lens is a perfect **circle**, and each lens can be easily rotated while in the eyeglass frame.). What harm, if any, would be done by rotating the lenses in the frame? What if the student was also astigmatic?*

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Lab Instructions

READ BEFORE COMING TO THE FIRST LAB

The physics laboratory is designed as a place for you to work with real examples of the theories you will see in lectures. You also might be introduced to material that isn't fully covered in lecture. While the labs are a lot of work, it is hoped they will be an enjoyable experience. The lab period is 3 hours long. You are expected to be present during the entire lab period unless excused by your instructor. The report for each lab will be due at 5PM the day following your lab period. If you work carefully and efficiently you should have enough time to complete most of the report before the end of the period. If you don't finish before you leave make sure to check with your instructor. You will be working in groups of 2 and occasionally 3, but no larger. Think of yourselves as a team, and assign tasks for each member. For example, in the first lab you will determine the index of refraction of a glass plate for many different angles of incidence. If three people work together, each lab partner can measure one angle that is different from the other partners. This way the group can observe a whole range of angles, while each person only makes one observation instead of three. Share the work load and **give credit** for work done, i.e. Ruth measured 20° , Erin measured 40° , etc. **Don't just copy the other person's work.** Give your **own** answers to questions. You should discuss solutions, but write the answers in your own words.

Lab Report Format

Lab reports should be written in a clear and concise manner. Don't expend a lot of energy making a picture-perfect formal report. Hand written reports are preferred typed reports. The labs are organized in sections. Work through each section in the order presented and numbering. Each section should include the following when appropriate:

- 1) **A DATA TABLE** showing clearly all quantities measured in the experiment, complete with units. Data should be entered directly in this table with no erasures. If you make a mistake draw one line through the bad point and include a note why you think it's a mistake.
- 2) **ANALYSIS** explaining clearly how your data was analyzed. Show all your calculations. Answers should first be given in algebraic form before plugging in numbers. When graphing, make sure the axes of your graphs are clearly labeled, including units. The graphs will often be the most important parts of the data analysis. Part of the analysis includes **UNCERTAINTY ESTIMATES** of all measurements and your final experimental results. This is to show how confident you are of your results.
- 3) **ANSWERS TO QUESTIONS**, answer any questions that are asked in the section.
- 4) **SUMMARIZE** your final result for each section by drawing a box around it.

Finally write a Summary for the entire lab. Write at least a few sentences about what the experiment did or did not prove. Sometimes a table will be helpful in summarizing your results. If your results did not come out as expected try to explain why they didn't. Use numbers as much as possible for these explanations. Many times there will be a lab demonstration or additional material, make sure to discuss this. State if you found everything as expected, or whether you were surprised by the results. Feedback about the lab, whether positive or negative, is also welcome here.

LABORATORY INSTRUCTIONS

The purpose of the laboratory report is to clearly demonstrate to your instructor that you understand the concepts presented in the laboratory. If you present your results in an organized form not only will you get a better grade, but it will be easier for you to remember the material.

Please STAPLE your report together. (There is a stapler located in the lab area.) **Always include your name and the name of your partner(s) in the report and your normal section day.** Also include your name or initials on every page in case the papers get separated.

Laboratory reports that are illegible or unintelligible will not be graded until they are rewritten in a readable manner. Don't worry about picture-perfect reports; it is possible to have plenty of mistakes crossed out and still be quite legible. The point is that the report should be easy to read. Putting boxes around the important results helps to direct the reader's eye.

Attendance

If you cannot come to your scheduled section, check with the instructor to arrange coming to another section or another time. If you cannot make up the lab during the week it is given you must arrange with the instructor **before the week is over**. Make-up labs outside the scheduled time will only be for an excusable absence and must be arranged **before** the end of the current lab week. All of the laboratories in the course schedule must be completed to receive a passing grade in the course.

E-Mail is a good way to get a message to an instructor about rescheduling a lab or arranging an appointment.

Quizzes

There will be three 10 minute quizzes given during the course. The quizzes will cover material specific to the methodology of the laboratory. They quizzes will be given at the beginning of the scheduled lab period at appropriate times during the course.

Grading

Your final grade will be a combination of your lab reports (85%) and the quiz grades (15%).

Reports turned in late will be **accepted at the discretion of the instructor**, and there will be a reduction in grade of 1/2 point per day late.

All laboratories and quizzes must be completed to receive a grade in the course.

Excel

The Excel spreadsheet program will be used to analyze data in many of the Physics 106/8 lab exercises. Figure 3 is a sample of an Excel worksheet. When creating worksheets for the lab, you should use a format very similar to the one shown in Figure 3. **Please note that the worksheet includes the name(s) of the person(s) who created it.** During lab, many documents will be printed on one printer. It is important that your name(s) appear on your document, otherwise you might pick up the wrong document from the printer.

Figure 4 shows a sample graph where Excel has fit a straight line to the data; the equation of the line (and the R^2 value) appears on the graph. When creating graphs in the lab, you should use a format very similar to the one shown. Please note that the graphs; include the name(s) of the person(s) who created them, that the axes are labeled, and the units are specified.

Sample Physics 106/8 Excel Worksheet

							Sample Excel Spreadsheet for Physics 106
							Comments
							(not needed on your report)
Hooke's Law Lab							<---- Name of Lab
Physics 106							
George Caplan							<---- Your Name(s)
1/8/2003							<---- Date
							<---- Blank Line
Symbol	m	M	F	x	d		
Dimension	mass	mass	force	length	length		
Units	<i>g</i>	<i>kg</i>	<i>N</i>	<i>cm</i>	<i>m</i>		<---- Note Italics
Calculation	Meas'd	m/1000	F=M*9.8	Meas'd	d=x/100		
Uncertainty	+/- 1	+/- .001	+/- .1	+/- .1	+/- .001		<---- Use only if uncertainty is same for each entry in col.
							<---- Blank Line
	100	0.10	0.98	10.0	0.100		<---- Measured values are bold
	200	0.20	1.96	16.4	0.164		<---- Calculated values are not bold
	300	0.30	2.94	20.0	0.200		
	400	0.40	3.92	25.0	0.250		<---- Gridlines are turned on
	500	0.50	4.9	28.7	0.287		
	600	0.60	5.88	34.9	0.349		

Figure 3 – Sample Physics 106/8 Excel Worksheet.

If you do not know how to create worksheets and graphs (also called “charts” in the Excel documentation) like these, your instructor can help you to learn how. Also, the Wellesley College chemistry department has some very nice Excel tutorials at their Web site. The tutorials can be found at:

<http://www.wellesley.edu/Chemistry/Flick/excel1.html>

and

<http://www.wellesley.edu/Chemistry/stats/form1.html>

Sample Physics 106/8 Graph With a Line Fit to the Data

Force vs. Distance (George Caplan) (Phyiscs 106 Sample)

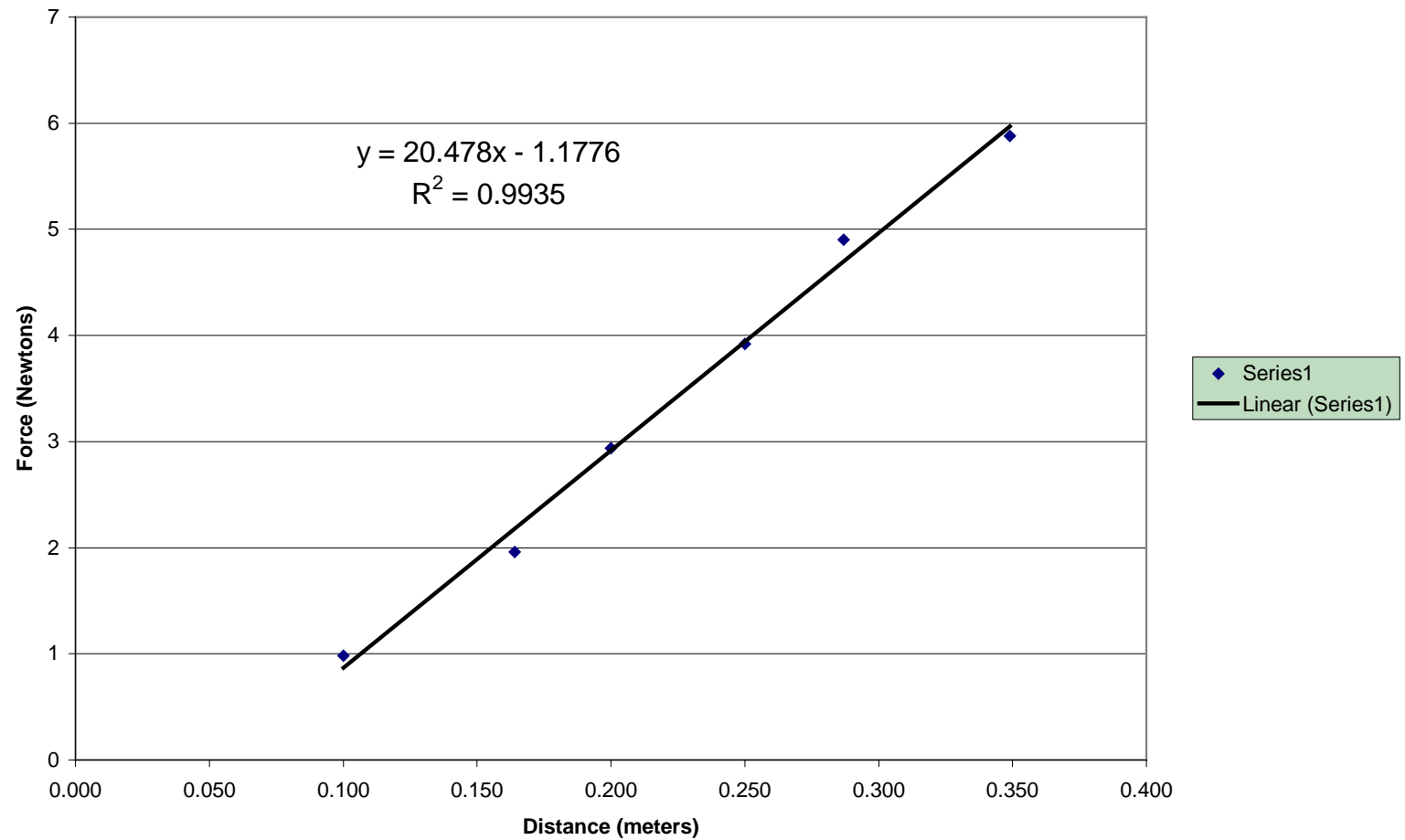


Figure 4 – *Sample Physics 106/8 Graph With a Line Fit to the Data. Note graphs should always be printed to take up the FULL page of paper. This is so you can detect any points that might not be on the best fit line. Experimental Uncertainties*

Experimental Uncertainties

The physical sciences are not exact. The theories that are stated as facts are in reality based on experimental measurements. Historically, as measuring techniques improve, theories need to be modified to explain new experimental evidence. Science advances when there is an experimental observation that does not conform to the expected results. Every measurement has a finite precision or uncertainty. There comes a point at which the measurement becomes fuzzy or random. The size of the fuzziness is the uncertainty. So the million dollar question is, "How do we know when an experiment contradicts theory?" An experimental result disagrees with theory when the difference between the two is more than the estimated uncertainty. (In other words, the two don't overlap.) Following is an example which demonstrates the methodology of estimating uncertainties.

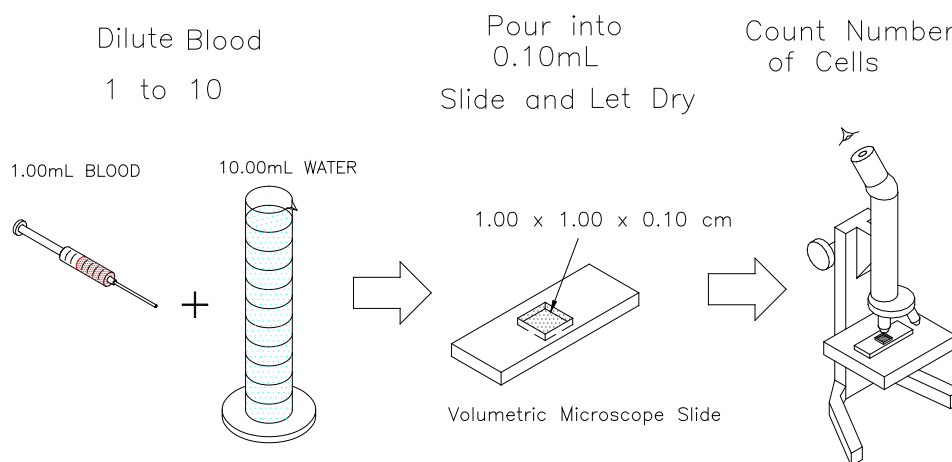


Figure 1 Schematic showing a method to count red blood cell density.

A new medical diagnostic depends on knowing the number of blood cells per unit volume of blood, which we will call the blood cell density. The density of blood cells in a group of volunteers is to be measured by the following procedure. A 1.00mL sample of blood is diluted with 10.00mL of water. (The dilution makes it easier to count the cells under a microscope.) The diluted sample is placed on a special microscope slide that has a precision well with a volume of 0.100mL. Printed on the base of the well is a grid to aid in counting the cells. Once the sample has dried, a technician counts the number of red blood cells. See Figure 1. The researcher will sample several healthy groups of volunteers of various ages and sexes. Normal levels having been established, it is hoped that red blood cell density can be used to diagnose some types of blood disorders. Before the experimenter proceeds, she is interested in knowing the range of values she should expect even if she had a uniform sample of blood, i.e. all of the same density. What should she do?

Think about the method used to measure blood cell density in this experiment. What are the potential sources of uncertainty in each step? What number should be assigned to each of these uncertainties? How these uncertainties be combined to estimate the final uncertainty in the blood cell density? While you are thinking about the above questions, let's digress for a moment and talk about types of uncertainties that you might expect to see in the laboratory.

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Types of Uncertainties In Measurements

Experimenters commonly group uncertainties into two types; *systematic* and *random*. Systematic uncertainties are repeatable uncertainties that are caused by some flaw in the experiment. The flaw could be:

- a) Using an instrument incorrectly or using an instrument that is out of calibration.
- b) Using an incorrect theory or method to interpret the data.
- c) Taking the data using an incorrect technique.

Ideally there is no excuse for systematic uncertainties in an experiment. Sound laboratory technique requires that all systematic uncertainties are eliminated. Use the following steps to minimize systematic uncertainties:

1) Make sure equipment and technique are reliable. Read the manual and follow directions. Handle all instruments with care. Make sure you understand how the measuring device works. If you don't understand how a device works, ask your instructor.

2) Do independent measurements to double check. Example - If timing 25 periods of a pendulum. One experimenter measures $51.2\text{s} \pm 0.2$ the other measures 49.1 ± 0.2 . It looks like one of the experimenters made a mistake in counting the number of periods.

3) Make sure the data analysis is accurate.

4) Compare your measurements to a known standard to determine if there is a systematic uncertainty.

Generally, systematic uncertainties are ignored when estimating the uncertainty in a final result. This is because the only real way to determine these is by comparing a measurement to a known standard. Sometimes, because of equipment limitations, it is necessary to add in a contribution for systematic uncertainty. In the context of this course, your instructor will inform you if there is a need to add in an estimate for systematic uncertainties.

Random uncertainties are uncontrollable variations that appear when making measurements. These uncertainties will always be present in any measurement. Deciding upon the size of the uncertainty in a measurement is often the hardest thing about uncertainty analysis, but here are three steps that you should consider every time you make a measurement.

1) The smallest uncertainty is generally the size of the smallest division of your instrument. Example: the smallest division on a meter stick is 1mm or 0.001m. So the smallest uncertainty when using a meter stick is $\pm 0.001\text{m}$

2) Decide if you can really measure the value to the smallest division of the scale. If a value you are measuring is "fuzzy", try to measure the range of the value and divide the range by two to estimate the uncertainty. For example, a HeNe laser is used to trace the path of light as it enters a piece of glass. The angle of the light is then measured with a protractor that has divisions marked to 0.5° . The diameter of the laser beam is approximately 1mm, when projected onto the scale of the protractor it corresponds to an uncertainty of $\pm 1^\circ$.

3) Make two independent measurements of the same quantity. If the two measurements do not agree within the limits of the uncertainty, then take several measurements and average the values for the result. Estimate the uncertainty by using the standard deviation or take the largest reading minus the smallest (this is called *the range*) and divide it by two. Example, a stop watch measures time to 0.01s. However if several independent measurements are made the range of values are about 0.4s due to human reaction time. So the uncertainty would be $0.4/2 = 0.2\text{s}$.

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Let's look at the blood cell density experiment and apply the above ideas. First list what is measured: 1) the volume of blood, 2) the volume of water, 3) the volume of diluted blood, and 4) the number of cells counted in this volume. Each of these measured values has an uncertainty associated with it. It is your goal as an experimenter to provide a "reasonable estimate" of how accurately each quantity can be measured. For this example it is reasonable to assume that all the volumes can be determined to the precision of the measuring devices. This assumes of course that there is no systematic uncertainty associated with the equipment. Finally there is the count of the number of blood cells. While the technician is trained to count accurately mistakes can still be made, such as, counting a cell more than once or missing a cell. As the total number of cells counted increases, there is a greater probability that there will be a counting mistake, which leads to an uncertainty. One way to "measure" this uncertainty is to supply the technician with a sample of slides, all of which have the same number of cells per slide. After the slides have been counted, one could average the values and use the range (range = largest - smallest) of values divided by two as an estimate of the uncertainty. (Another approach would be to calculate a standard deviation for the number of blood cells and then use "two times the standard deviation" as the uncertainty. You will learn more about standard deviations in "The Simple Lens" lab this semester.) In addition the technician should be supplied with a range of the number of cells per slide. This provides a check to see if there is any correlation between the uncertainty versus the number counted. The experimenter does this and finds the following results;

Table of Uncertainty in Blood Count (D_n) vs. Counted Blood Cells (n)

D_n	n
3	100
10	300
14	500
31	1000
59	2000

A graph of D_n versus n yields a straight line through the origin. This tells the experimenter that the ratio of D_n to n is a constant. The constant is the slope of the line, which in this case is 0.030. While the technician makes more mistakes as she counts more cells, the fractional ratio of uncertainty to counted number of cells remains constant.

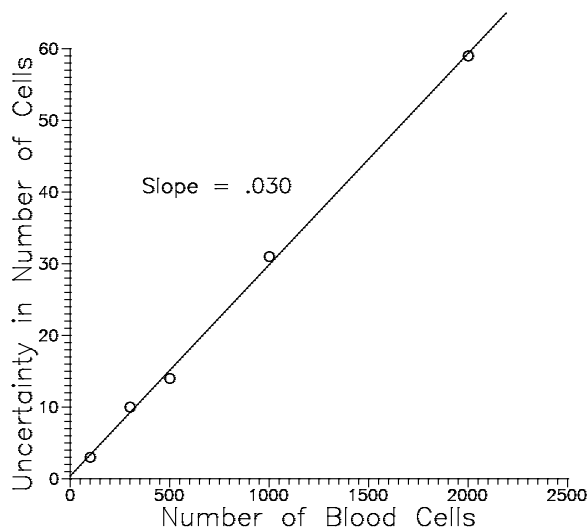


Figure 2 Graph of the uncertainty in number of blood cells counted as a function of the total number of cells.

Uncertainty Analysis - Propagation of Uncertainties

Now that there is an estimate for the uncertainty in each step of the blood density measurement the question becomes, "How do the uncertainties of the individual measurements combine to affect the uncertainty in the calculated result?" Answering this question involves the propagation of uncertainties and is an important laboratory skill.

One way to answer the question is to recalculate the result by varying all the measurements through their range of possible values. While this at first may seem the most straightforward, it is in fact the most time consuming in the long run. Example: A student

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measures the dimensions of an aluminum block, H , W , and L . Her values are: $H=11\pm 1\text{mm}$, $W=21\pm 1\text{mm}$, and $L= 34\pm 2\text{mm}$. She multiplies all of the values together to determine the volume and find it equal to 7854 mm^3 . If the largest possible values for all the dimensions are used to calculate the volume, then this should yield the largest possible volume. She does this and finds $V = 12 \times 22 \times 36 = 9504 \text{ mm}^3$. She finds the uncertainty in volume by taking the difference, $9504 - 7854 = 1650 \text{ mm}^3$. She then rounds the uncertainty in the volume to one significant figure and gets 2000 mm^3 . This tells her that the volume is significant to the thousands column and therefore she must round the volume to the nearest thousands place and gets $V=8000\pm 2000\text{mm}^3$.

This sounds easy, but think back to the measurement of blood cell density. How would you go about combining all of the uncertainties in each step? I hope you see the problem with this "simple" approach as the number of measurements increases and the complexity of the equations grow. The technique normally used involves some rules derived from differential calculus. (For those of you interested in learning more about how these rules are derived and how you use them, I suggest you read Chapters 1 and 3 in *An Introduction to Error Analysis, 2nd ed.* by John R. Taylor; it should be on reserve in the library.)

Rules For The Propagation of Uncertainties

<p style="text-align: center;">Let Δx be the uncertainty in x.</p> <p>1) If $f(x, y, z, \dots) = \frac{x \times y}{z \dots}$ Then:</p> $\frac{Df}{f} = \frac{Dx}{x} + \frac{Dy}{y} + \frac{Dz}{z}$ <p style="text-align: center;"><i>When multiplying or dividing, add the fractional uncertainties.</i></p> <p>2) If $f(x, y, z, \dots) = x + y - z + \dots$ Then:</p> $Df = Dx + Dy + Dz + \dots$ <p style="text-align: center;"><i>When adding or subtracting, add the absolute uncertainties.</i></p> <p>3) If $f(x) = x^n$ Then:</p> $\frac{Df}{f} = n \times \frac{Dx}{x}$ <p style="text-align: center;"><i>When raising a variable to a power, multiply the fractional uncertainty by the absolute value of the power.</i></p> <p>4) If $f(x) = a \times x$ Then:</p> $Df = a \times Dx$ <p style="text-align: center;"><i>When multiplying by a constant, the uncertainty scales proportionally.</i></p> <p>5) If $f(x) = \sin(x)$ Then:</p> $\frac{Df}{f} = \frac{Dx}{\tan(x)}$ <p style="text-align: center;"><i>Where Δx is in radians.</i></p>

Table 1

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Notice that the uncertainties, whether *absolute* or *fractional*, always **add** together. The idea behind this is that you are interested in the maximum possible effect the uncertainties can have on the final result. When you use the rules on complicated functions, you must break the function up into parts and apply the rules one at a time as appropriate. This is very similar to the "chain rule" used to take derivatives in calculus. The sample problems at the back of this section will demonstrate this.

Now, back to the problem about the density of blood cells. Before you can propagate the uncertainties, you must have an equation that contains all the variables that you use to calculate your final result. So let's assign variable names to each of the values measured in finding the blood cell density. First there is the volume of the sample of blood; call this V_1 . This is diluted with a volume of water, V_2 . Then there is the volume of diluted sample that is counted, call this V_3 . Finally there is the number of cells counted, n . The blood cell density will be given the product of the density of the diluted sample n/V_3 times the factor by which the blood sample has been diluted $(V_1+V_2)/V_1$ which for large dilutions is approximately V_1/V_2 . Therefore the blood density is given by

$$r = \frac{n \times V_2}{V_1 \times V_3}.$$

The above density is the product of two numbers divided by the product of two more numbers. This looks like Rule 1 so the *fractional uncertainty* in the density, Dr/r , will be the sum of the fractional uncertainties of all the terms;

$$\frac{Dr}{r} = \frac{DV_1}{V_1} + \frac{DV_2}{V_2} + \frac{DV_3}{V_3} + \frac{Dn}{n}$$

$$\frac{Dr}{r} = \frac{.01}{1.00} + \frac{.01}{10.00} + \frac{.001}{.100} + .03$$

$$\frac{Dr}{r} = .01 + .001 + .01 + .03$$

$$\frac{Dr}{r} = 0.051 \text{ } \approx 5.1\%$$

This information tells the experimenter that even if she had a uniform sample of blood she should expect a 5% variation in the density, independent of any variation in the sample. Now before ever doing the experiment, she may decide that this technique is not sensitive enough to detect the variations in blood cell density that she is looking for. For example, suppose she were interested in a 1% variation in blood cell density; this technique would clearly not be sensitive enough to measure the variations she was expecting. If the experimenter wanted to improve the sensitivity of this technique, what would she have to do? The individual terms in the above equation can provide a key to finding what needs to be measured more carefully to make the results better. Since the fractional uncertainty in V_1 , V_3 , and n are all 1% or greater, each of these measurements would have to be made to a higher degree of accuracy, say 0.1%, in order to make the uncertainty in the cell density less than 1%. However, no matter how many cells are counted the fractional uncertainty is always going to be 3%. From this analysis the experimenter must decide that this technique is just not going to achieve the accuracy she desires unless she

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improves the counting technique. So, uncertainty analysis not only can tell you how much variation you should expect in an experiment; it also can help you decide how to make your experimental results better.

Numerically Calculating Uncertainties

Sometimes the formulas you use might not fit any of the forms shown in Table 1. In this case you need to calculate the uncertainty directly

$$Df = |f(x + Dx) - f(x)|. \quad (12)$$

For more variables you just add the absolute value of all of the individual changes together

$$Df = |f(x + Dx, y, z) - f(x, y, z)| + |f(x, y + Dy, z) - f(x, y, z)| + |f(x, y, z + Dz) - f(x, y, z)|. \quad (13)$$

With the proliferation of personal computers and spreadsheet software it may be easier to calculate uncertainties using the above formula instead of the rules laid out in Table 1.

As an example lets look at the function

$$f = \frac{1}{(1 - x^2)}.$$

where $x = 2.51 \pm 0.02$. Applying the rules in Table 1 is more difficult than calculating the uncertainty using equation 12.

$$f(x) = \frac{1}{(1 - 2.51^2)} = - .18868$$

$$f(x + Dx) = \frac{1}{(1 - 2.53^2)} = - .18515.$$

So the uncertainty is the absolute value of the difference of the above which is 0.004 when rounded to 1 significant figure. The final result would be reported as $f = -0.189 \pm 0.004$.

Significant Figures

Significant figures refers to the number of meaningful digits in a number. Electronic calculators and computers will yield an abundance of digits, but not necessarily all of them will have significance. The normal "rule-of-thumb" method says, "The result of a calculation should have no more significant figures than the number with the least significant figures used in a calculation." This rule will not be used in the context of the lab because it is not always true. Instead you will use the calculated uncertainty to tell you which decimal place is the last one that has any significance. Here are some guidelines to use when reporting significant figures in your lab reports.

1) Leading zeros are never significant. Imbedded zeros are always significant. Trailing zeros are significant only if the decimal place is specified. Example, all these numbers have 3 significant figures; 0.000463, 378,000, 100 ± 1 .

2) A number written with no uncertainty is assumed to have an uncertainty of \pm the Least Significant Digit. (± 1 LSD) Example: 156.34 has uncertainty of ± 0.01 , 1200 has an uncertainty of ± 100 , however 1200 ± 1 has four significant figures.

3) Keep only one significant digit in the uncertainty. Example: Your calculator gives you a value of 0.013333 for your uncertainty. Rounding the uncertainty to one significant figure yields 0.01. An uncertainty of 313.567 should be rounded to 300.

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4) Round the result to the decimal column pointed to by the uncertainty. Example: The result 345.0678 ± 0.04 rounds to 345.07 ± 0.04 . The result 12123.4 ± 300 rounds to 12100 ± 300 .

5) Always express the uncertainty and the result to the same power of ten. In other words, the units for the value and uncertainty should be the same. Example: The result $45.67 \times 10^2 \pm 2$ should be written as a) $(45.67 \pm 0.02) \times 10^2$ or b) 4567 ± 2 .

An example to consider:

A museum guard proudly told visitors that the dinosaur bones on display were "60,000,005 years old." When asked how the age could be known so precisely, the guard replied, "I don't know, but when I came to work here five years ago they told me that the bones were 60 million years old." (This humorous lesson in significant digits came from John McGervey's book *Probabilities in Everyday Life*, 1986, Nelson-Hall, Inc.)

Summary

Every measurement has an uncertainty associated with it. The uncertainty is a measure of your confidence in the result. A small uncertainty implies a high confidence. Measured or calculated quantities agree if their values overlap within their uncertainties. Every time an experimental measurement is done, there should be some form of uncertainty estimate made for the results. The first step in propagating uncertainties is to write an algebraic expression for your answer in terms of the quantities that you have measured. Then use rules 1) through 5) from Table 1 to write an expression for the absolute or fractional uncertainty in the answer. Use this expression and plug in the numbers from your data table to calculate the absolute uncertainty. Finally, express the answer with the uncertainty included with the correct number of significant digits. Doing these calculations should be simple and straight forward, if you find yourself spending "all" your time doing uncertainty analysis please ask your instructor for guidance.

References: Books About Estimating Uncertainties

Level	Author	Title or <i>url</i>
Beginner	William Lichten	<i>Data and Error Analysis, 2nd ed.</i>
Beginner	Yardley Beers	<i>Introduction to the Theory of Error</i>
Intermediate	Clifford E. Swartz	<i>Used Math; For The First Two Years of College Science</i>
Intermediate	John R. Taylor	<i>An Introduction to Error Analysis, 2nd ed.</i>
Intermediate	NIST	physics.nist.gov/cuu/Uncertainty

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Sample Problems

1) The index of refraction in air is given by

$$n = \frac{\sin(q_r)}{\sin(q_i)},$$

where q_i is the angle of incidence and q_r is the angle of refraction. Alessondra measured $q_i=30\pm 1^\circ$ and $q_r=45\pm 1^\circ$ for a glass plate.

- a) Write an expression for the fractional uncertainty in the index of refraction $\frac{Dn}{n}$.
- b) What should Alessondra report for the index of refraction for this plate?

2) The lens makers equation $\frac{1}{f} = \frac{1}{p} + \frac{1}{i}$ solved for the focal length is

$$f = \frac{p \cdot i}{(p + i)}$$

where i is the image distance and p is the object distance.

Julie measures $p= 11.2\pm 0.5\text{cm}$ and $i = 21.3\pm 0.5 \text{ cm}$.

- a) Write an expression for the fractional uncertainty in the focal length, $\frac{df}{f}$.
- b) What should Julie report for the focal length?

3) The angle of total internal reflection q_c for a glass plate in air is given by

$$q_c = \arcsin\left(\frac{1}{n}\right)$$

where n is the index of refraction of the glass. Elena has determined that the index of refraction for her glass plate is $n=1.72\pm 0.05$. She also made the following measurements for the angle of total internal reflection: 36° , 34° , 33° , 35° , and 33° .

- a) What should the angle of total internal reflection be based on the index of refraction n ?
- b) What is the uncertainty in q_c as characterized by the standard deviation of the measured angles?
- c) Do these values overlap within their uncertainties?

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Solutions To Sample Problems

1) a) $n = \frac{\sin(q_r)}{\sin(q_i)}$ looks like a combination of Rules 1 and 4. Applying Rule 1:

$$\frac{Dn}{n} = \frac{D\sin(q_i)}{\sin(q_i)} + \frac{D\sin(q_r)}{\sin(q_r)}$$

Then Rule 4:

$$\frac{Dn}{n} = \frac{Dq_i}{\tan(q_i)} + \frac{Dq_r}{\tan(q_r)}$$

b) First find the index of refraction n

$$n = \frac{\sin(45)}{\sin(30)} = \frac{0.7071}{0.5000} = 1.414 \text{ (leave plenty of digits for rounding later)}$$

Now find the fractional uncertainty in n . Converting $Dq = \pm 1^\circ$ to radians $= \pi/180 = 0.017$ so.

$$\frac{Dn}{n} = \frac{0.017}{\tan(30)} + \frac{0.017}{\tan(45)} = 0.029 + 0.017 = 0.046 = 4.6\%$$

The absolute uncertainty is the above times the index of refraction:

$$Dn = \frac{Dn}{n} \times n = 0.046 \times 1.41 = 0.065 \approx 0.07 \text{ (round uncertainty to 1 significant figure)}$$

This means the index of refraction is only good to the 1/100ths place. So the final value for the index is $n = 1.41 \pm 0.07$.

2) a) First use Rule 2. However, the third term can be ignored because d_o and d_i are not independent of each other, so

$$\frac{Df}{f} = \frac{Dd_i}{d_i} + \frac{Dd_o}{d_o} + \frac{D(d_i + d_o)}{d_i + d_o} \quad \textcircled{R} \quad \frac{Df}{f} = \frac{Dd_i}{d_i} + \frac{Dd_i}{d_i}$$

b) $f = \frac{21.3 \times 1.2}{21.3 + 11.2} = 7.3403$ (Always keep plenty of digits for rounding off later).

$$\frac{Df}{f} = \frac{0.5}{21.3} + \frac{0.5}{11.2} = 0.023 + 0.045 = 0.068 \approx 6.8\%$$

$$Df = 0.068 \times 7.34 = 0.499 \approx 0.5 \text{ cm}$$

Therefore; $f = 7.3 \pm 0.3$ cm.

(The rule of thumb would have said the result should have three sig. figs.)

3) a) The equation for total internal reflection doesn't fit any of the rules in table 1 so use eq. (12)

$$Df = |f(x + Dx) - f(x)| = \left| \arcsin\left(\frac{1}{1.77}\right) - \arcsin\left(\frac{1}{1.72}\right) \right| = |34.4 - 35.5| = 1.1 \approx 1$$

The critical angle should be reported as $q_c = 36 \pm 1^\circ$.

b) Take an average of the angle to get the best value. $q_{\text{ave}} = (36 + 34 + 36 + 35 + 33 + 34)/6 = 34.8$.

Use standard deviation for uncertainty in angle. $s = 0.98 \approx 1$ (Rounding uncertainty to 1 sig. fig.)

so $q_c = 35 \pm 1^\circ$

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Experiment 1 - Reflection and Refraction of Light

A helium-neon laser is used to trace the path of light as it passes through a glass plate. A protractor is used to measure the angles so that Snell's Law can be tested. Total internal reflection will also be investigated.

Apparatus:

Helium-neon laser, glass plates, wooden board with leveling screws, paper, pins, ruler, tape, pencil, and protractor.

***** WARNING *****

DO NOT LOOK INTO THE LASER BEAM!

BE CAREFUL NOT TO LET REFLECTIONS ENTER YOUR EYE.

Introduction:

A laser emits light rays that are all nearly parallel to each other. The beam is said to be well *collimated*. This light is a very good approximation to the ideal light-ray used in theories that describe the behavior of light. Contrast laser light with that from an incandescent bulb, where the rays radiate in all directions. The light from the laser is also extremely bright, so it is easy to track in a lighted room. In a darkened room the light can be tracked though glass and air as it scatters off dust particles in the air and imperfections in the glass.

You will use the laser to trace light rays as they change direction when passing through transparent media. With the measurements you make you will test the law of reflection and Snell's law of refraction. You will also investigate total internal reflection. Figure 1 is a side view of the setup you will use in this lab. A piece of paper is taped to a pin board and a glass plate is laid down on the paper. The height of the pin board should be adjusted with the leveling screws so that the laser beam just skims over the top of the paper and hits the glass plate in the middle.

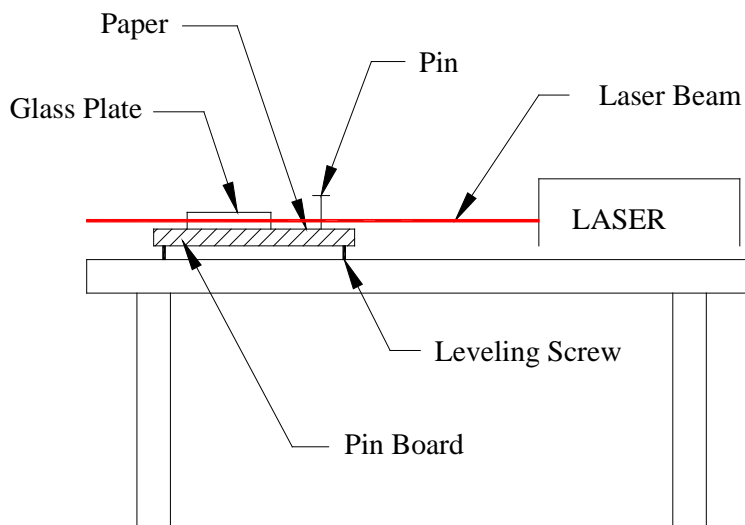


Figure 1 Side view of the equipment used in this experiment.

Figure 2 shows a top view of what happens to the light rays before and after they strike the glass plate. By moving a pin around the surface of the paper, the path of the light can be traced as it enters and exits the glass. Small pin marks are made in the paper to locate the center

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of the beam. These marks can then be connected with a pencil and ruler, tracing out the path of the light rays. The outline of the glass plate is traced, the plate is removed, and the angles of the light rays are measured with a protractor. You can use your tracings for both Parts 1 and 2.

The Reflection of Light

1) Turn on the laser and make sure the shutter is open so that the beam is visible. The shutter is a small metal tab on the side of the threaded end of the laser. To extend the life of the laser, the beam should be turned on and off by using the shutter instead of switching the power on and off. Place the square glass plate on a piece of paper on the pin board so that the laser beam strikes one of the polished sides. (The polished sides appear clear, not rough.) Rotate the plate so that the angle of incidence is approximately 20° . Now, use pins to secure the plate to the paper so that it can not move. (You don't want the plate moving while making your measurements.) Using a sharp pencil, trace an outline of the plate. Be careful to get the lines parallel and as close as possible to the surface of the glass.

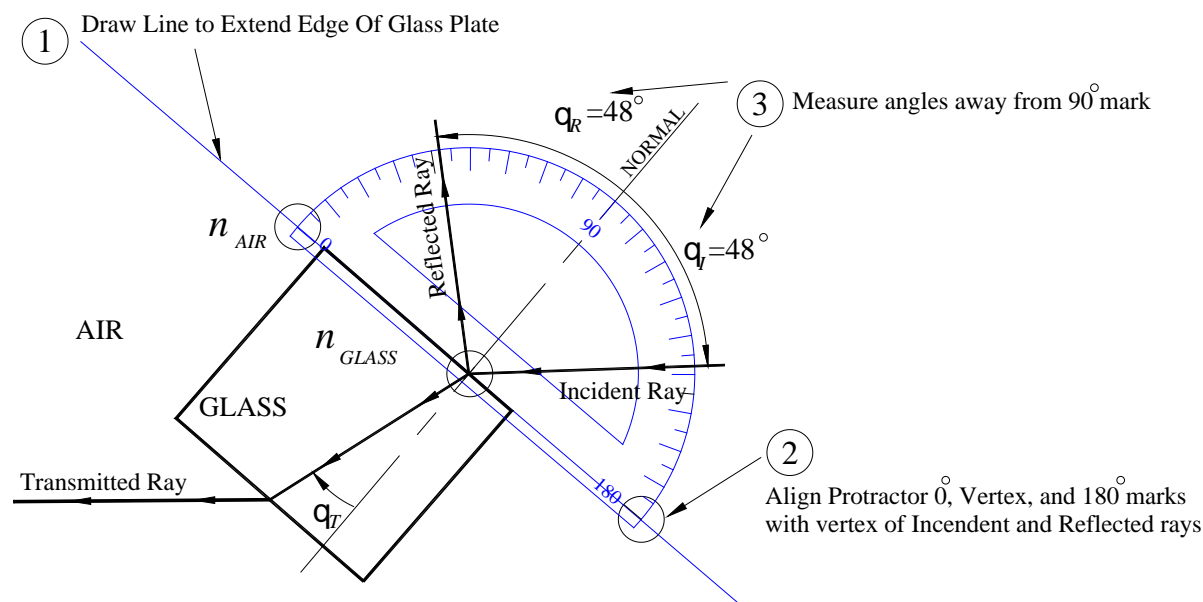


Figure 2 Diagram showing the typical path of light rays as they enter and leave a glass plate.

2) Use pins to trace out the path of the laser light ray incident to the glass. Take a pin and, while holding it perpendicular to the plane of the paper, move it around the paper where you think the laser beam might be. When the pin enters the beam, you should see a bright reflection on the paper. Try to center the pin in the beam and then make a small pinprick in the paper. Then move the pin along the expected beam path and make another pinprick in the center of the beam. The two pinpricks define points along the path of the beam. Use a ruler and pencil to connect the points. The line drawn should extend to the surface of the glass plate. Clearly label the direction of travel of the ray. Repeat the above procedure for the reflected ray and the transmitted ray. See Figure 2.

3) When all three rays are defined remove the plate from the paper and close the shutter on the laser. Measure the angle of incidence (q_i) and the angle of reflection (q_r) from your tracings. How accurately do you feel you can determine these angles? Briefly state your reasons for

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picking this quantity. Hint: The uncertainty, Δq , is probably less than 10° because you can draw better than that. However the uncertainty is probably greater than 0.5° because you might make mistakes tracing the rays.

4) The Law of Reflection states that the angle of incidence equals the angle of reflection:

$$q_I = q_R \quad (1)$$

Does your data support this law within your uncertainties?

5) Repeat parts 1) through 4) using angles of incidence of approximately 40° and 60° . If you are working with partners, each partner should make at least one measurement on her own and then you should share results. Try to vary the angle of incidence over as wide a range as possible. Note: Use a separate sheet of paper for each angle; otherwise, the tracings become very confusing.

The Refraction Of Light

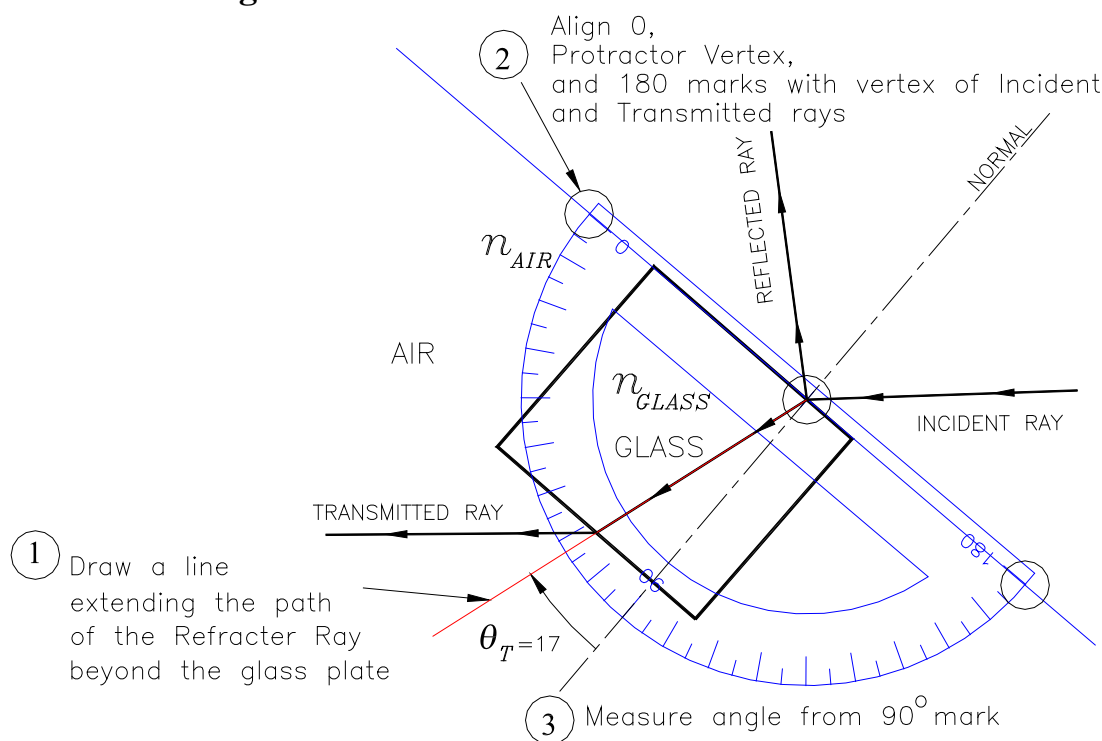


Figure 3 Diagram showing how to measure the angle of refraction inside the glass plate.

6) For the three sets of data from above, trace out the path of the refracted ray. You know where the light went in (the incident ray) and where it came out (the transmitted ray), so you should be able to trace the path it must have taken in the glass. Use a protractor to measure the angle of refraction, q_T . You may need to extend the refracted ray beyond the boundaries of the glass plate in order to measure the angle with the protractor. See Figure 2. Remember these angles are measured from the normal.

7) Snell's Law states that the ratio of indexes of refraction is equal to the ratio of the sines of the angles of incidence and refraction;

$$\frac{n_{GLASS}}{n_{AIR}} = \frac{\sin q_{AIR}}{\sin q_{GLASS}} = \frac{\sin q_I}{\sin q_T} \quad (2)$$

Calculate the ratio n_{GLASS}/n_{AIR} for your piece of glass for each trial.

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The index of refraction of air is very close to 1.000, so your values from above are really just the index of refraction for your glass plate. Summarize your data in a table showing; the angle of incidence, the angle of refraction, and the index of refraction with uncertainty. Does your data support Snell's Law? In other words, are all the indexes equal within their uncertainties? If you answer "no" to this question or if you have one measurement that doesn't quite fit, what might have gone wrong?

8) Based on your measurements, what is the best value (including uncertainty) for the index of refraction for your piece of glass? Explain why you quote the value you do. For example, is it best to average all values or use just one or two? What makes one measurement better than another?

Total Internal Reflection

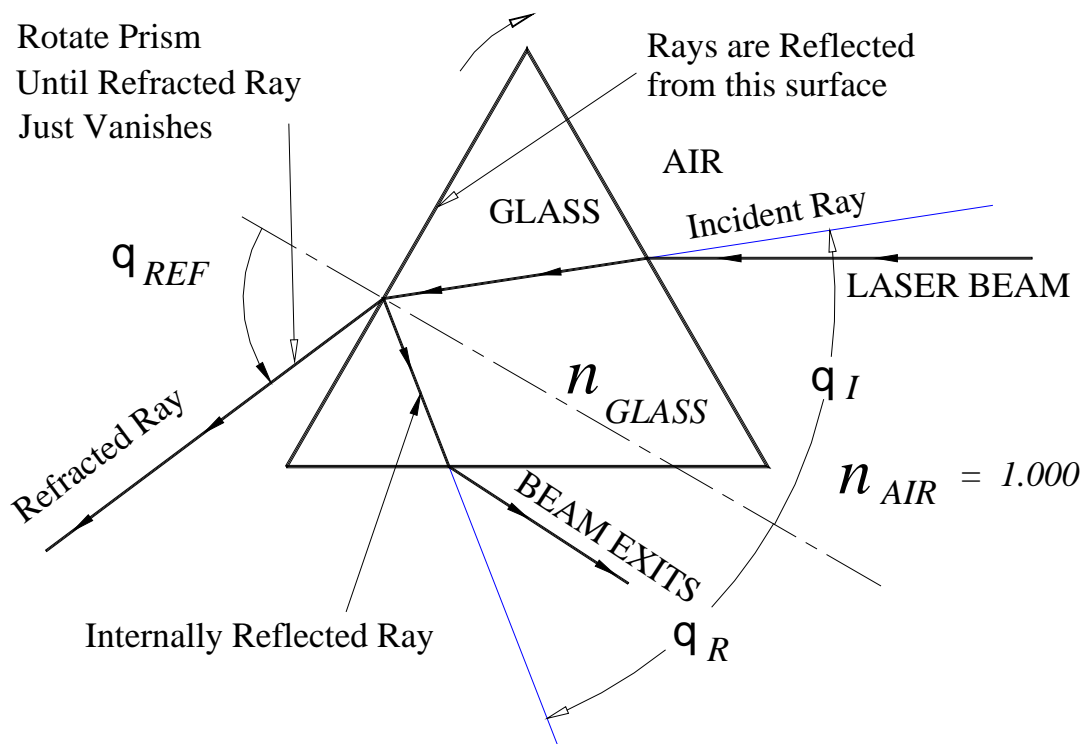


Figure 4 Diagram showing how the rays enter and leave a glass prism for measurement of total internal reflection. Notice how the internally reflected rays need to be extended in order to measure the angle inside of the prism.

In this part of the experiment you will investigate what happens as a light ray goes from a region of high index of refraction to a region of low index of refraction. The angles of incidence, refraction, and reflection all refer to the GLASS to AIR surface located inside the prism. See Figure 4.

9) Set up the triangular shaped glass plate for ray tracing as you did for the square glass previously.

10) Position the glass triangle and the laser as indicated in Figure 4.

11) By rotating the prism you can vary the angle of incidence, q_I . Notice that as the angle of incidence increases, the angle of refraction, q_{REF} , goes to 90° . At this point the refracted beam suddenly vanishes. All the light is going into the reflected beam and is totally reflected off the glass to air interface. When you have the prism rotated to the point where the refracted beam just

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vanishes, pin the triangle and trace the outline and all of the rays entering and exiting the glass; include the spot where the beam reflects off the inside edge of the triangle. The angle of incidence (q_i) and the angle of reflection (q_r) are now equal to the critical angle, q_c . The critical angle for total internal reflection is given by:

$$q_c = \text{Arc sin} \frac{n_A}{n_G} \quad \text{Where } n_G > n_A \quad (3)$$

12) From your ray tracings determine q_c . (This angle is just q_i and q_r in Figure 4 when the transmitted ray just vanishes.)

Calculate the expected value of q_c using Equation 3 and your previous best estimate of the index of refraction of the glass plate. The glass triangle is made from the same type of glass as the rectangular plate. Does your measured value of q_c agree with the predicted value? Don't forget to estimate the accuracy of your values.

Angle of Minimum Deviation

The angle of deviation d as shown in Figure 5 is defined as the angle between the ray incident on a prism and the Deviated Ray exiting the prism. If the light starts out at normal incidence to the face of the prism the Deviated Ray will be deflected by a large angle. If the prism as shown in Figure 5 is rotated in the counter-clockwise direction the angle of deviation will begin to decrease. As the prism is further rotated the angle d will reach a minimum value d_m and then will begin to increase.

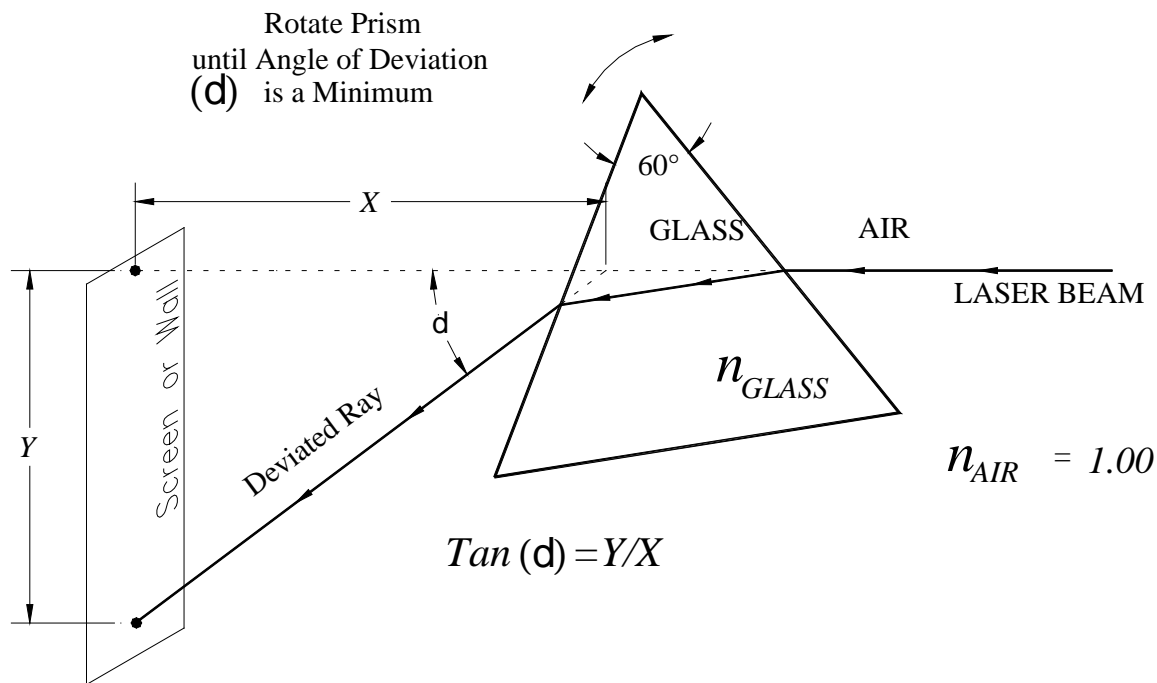


Figure 5 Diagram showing how to measure the angle of minimum deviation.

One can derive an expression for d in terms of the incident angle, the exiting angle, the angle q of the prism, and the index of refraction of the prism. This expression can then be manipulated so that the incident and exiting angles drop out. This happens when d is at a minimum and yields an expression for the index of refraction n in terms of d_m and q

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$$n = \frac{\sin\left[\frac{1}{2}(\mathbf{d}_m + \mathbf{q})\right]}{\sin\left(\frac{1}{2}\mathbf{q}\right)}. \quad (4)$$

13) Set up the laser to project onto the wall or onto a screen and mark this position. Now place the prism so the beam is deviated by the laser as shown in Figure 5. Rotate the prism back and forth while watching the position of the deviated beam. Rotate the prism until the angle of deviation is a minimum. Measure the distance from the prism to the screen (X) and the distance of deviation (Y). Use these values to determine the angle of deviation, \mathbf{d}_m . Then, using 60° for the angle of the prism \mathbf{q} and using the \mathbf{d} that you measured, calculate the index of refraction, n , from Equation 4.

What happens in Equation 4 when the angle \mathbf{d} goes to zero? Does this make sense?

References

Angle of minimum deviation may not be covered in lecture. So, here are some references.

Halliday, Resnick and Walker, *Fundamentals of Physics*, 7th ed., problems 53 on page 918 and problem 62 on page 919.

Hecht, *Optics*, 4th ed., pages 187 – 189. (Also in 3rd ed. pages 189 – 191.)

See

http://people.uncw.edu/ganl/fizix102labs/lab10dispersion2_s2005_102.pdf

Experiment 2 - The Simple Lens

In this lab you will investigate how simple lenses form images. You will determine the focal lengths of converging and diverging lenses in two different ways. The first method will be to find the point of focus of parallel beams of light passing through the lens. The second method uses the thin lens equation and averages a large number of measurements. You will also study what happens when you average a set of data and how to use the standard deviation as a measure of uncertainty.

Apparatus:

Optical bench, object source, projection card, and convex and diverging lenses.

Introduction

Lenses

A **converging lens** is a lens that bends entering rays of light towards each other. It is thicker in the center than it is at the edge. The focal length of a converging lens is defined as the distance from the center of the lens to the image formed by rays of light entering parallel to the lens, i.e. for an object infinitely far away. See Figure 1. A converging lens is capable of forming a real image of any object that is at a distance greater than one focal length away from the lens. A **diverging lens** is a lens that bends entering rays of light away from each other. It is thinner in the middle than at the edge. A diverging lens alone is not capable of forming a real image of an object. The focal length of a diverging lens is defined as negative the value of the distance from the center of the lens to where the extension of a parallel ray entering the lens crosses the optical axis. See Figure 1.

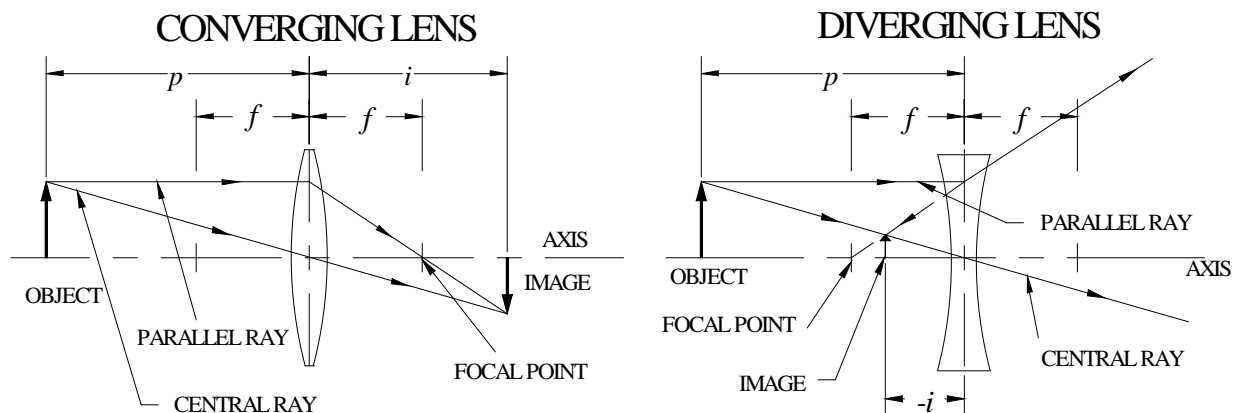


Figure 1 Ray tracings for a converging and diverging lenses.

The thin lens equation:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{i} \text{ or } f = \frac{(p \times i)}{(p + i)} \quad (1)$$

describes the relation between the object distance p , the image distance i , and the focal length f of the lens. Note that whenever the image distance is negative, the image formed will be **virtual**. A virtual image cannot be projected on a screen. Also notice that when the object distance goes to infinity, $1/p = 0$, and $f = i$. In other words, as p (the object distance) becomes very large, i (the image distance) approaches f .

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Mean and Standard Deviation

The measuring process is inevitably associated with random variations due to uncertainty. If many independent measurements are averaged, the result is a number that represents the best value for all the measurements. The averaging process smoothes out random variations due to the uncertainty of each measurement. The average, X_m , is just the sum of all the measurements divided by the total number of measurements:

$$X_m = \frac{1}{N} \sum_{i=1}^N X_i \quad (2)$$

In Eq. 2, N is the number of measurements and the X_i 's are the individual measurements. The uncertainty is reduced because, on the average, we expect an equal probability of any measurement being too big or too small. In other words, the average deviation for a large set of measurements is zero. The deviation, D_i , of any measurement is defined as the difference between itself and the mean

$$D_i = X_i - X_m.$$

The average deviation, \overline{DX}_m , is just the average of the above deviations:

$$\overline{DX}_m = \frac{\sum_{i=1}^N (D_i)}{N} = \frac{1}{N} \sum_{i=1}^N (X_m - X_i). \quad (3)$$

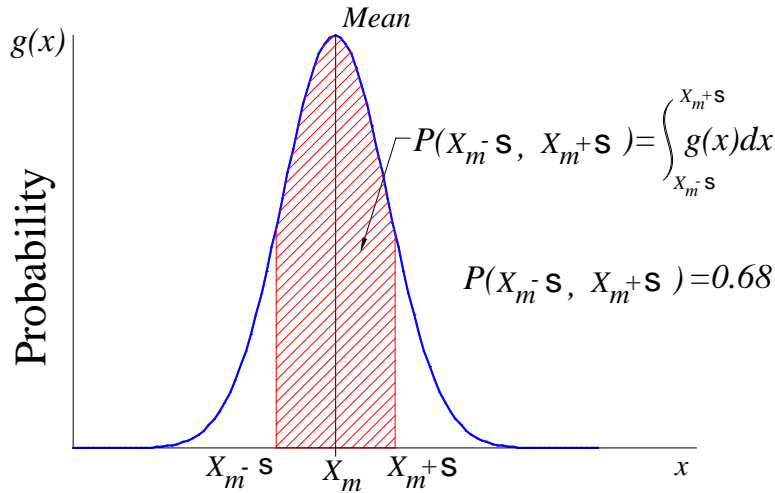


Figure 2 Probability distribution for an ideal data set.

If you made a plot of the probability distribution versus the measured values for a large set of measurements, you would probably get a curve that looks like Figure 2. This curve is known as a **Gaussian** or **Normal** distribution, and it is often assumed that most random data fits this curve. In general, the larger the number of data points, the closer the actual probability distribution will approximate a Gaussian. The probability of any measurement falling between x_1 and x_2 is found by calculating the area under the curve between these two points. The area is found by integrating the function from x_1 to x_2 . If $g(x)$ is the normalized probability distribution then the integral of $g(x)$ from $-\infty$ to ∞ must be 1 since there is a 100% chance of measuring something. Calculating definite integrals and looking at probability distributions is all well and good, but how can we easily estimate the probability of a measurement falling within a certain range for any data set?

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We'd like some simple way to measure the range of deviations for any data set from the average, and we'd like to relate this to the probability of our measurements falling within that range. Remember, the average deviation is zero. Therefore, to calculate the uncertainties, we look at the average of the square of the deviations which is always positive. The standard deviation, s , is defined to be the square root of the averaged squared deviation

$$s = \sqrt{\frac{\sum_{i=1}^N (X_i - X_m)^2}{N - 1}}. \quad (4)$$

The quantity s (*sigma*) is called the **standard deviation**. (Although you might expect a divisor of N , $N-1$ is the correct number of **differences**.) For a Gaussian distribution the probability of any measurement falling within \pm one standard deviation of the mean is approximately 68%. The probability of the measurement being within \pm two standard deviations is approximately 95%. Remember: These probability estimates come from assuming that the distribution of the data set matches that of a Gaussian distribution. If your data set doesn't look like a Gaussian distribution, then the range of $X_m \pm s$ will have a probability different than 68%. For example, let's say that you take 25 measurements of the focal length of a lens. How many of these measurements should be within $X_m \pm s$ of the average value for the focal length? $N_s = 0.68 \times N_{\text{TOTAL}} = 16.8 \approx 17$. So roughly 17 out of the 25 measurements should be within one standard deviation of the average focal length. If there is a substantial difference, then the probability distribution of this data set may not be Gaussian and the confidence level will then be different than 68%.

Lenses On The Optical Bench

Please treat the lenses with care. Hold them only by their edges. If you have trouble getting the lenses to stay in the lens holders or if you have difficulty using the lens holder, ask your instructor.

Measuring focal length by imaging an object at infinity.

1) **Measuring a converging lens:** Take the optical bench with the screen and converging lens to the walkway overlooking the Focus in the Science Center. Set your optical bench on the floor and in a location to not block traffic. Use the medium thick lens from the lens box (#2) to form a sharp image on the screen of the large windows at the west end of the building. Note that the image is inverted. (It is also in color.) The distance from the screen to the lens is now the focal length of the lens. Estimate your uncertainty in determining the focal length as follows. First, move the lens closer to the screen until the image **just starts to go out of focus**, record this distance. Now move the lens away from the screen through the sharpest point until it again just starts to go out of focus, record this distance. The uncertainty in your ability to measure the focal length of the lens is now found by taking the absolute value of the difference of these two distances and dividing by two. This is estimating the uncertainty by taking half the range over which you can tell when the image is in focus.

2) **Measuring a diverging lens:** Put the diverging lens (#4) in the lens holder on the optical bench. Try to form an image on the card, just as you did for the converging lens. Briefly describe what happens. Place the converging lens (#2) and the diverging lens in the holder so that they are touching. You should now be able to form an image on the screen. Record the distance from the diverging lens to the card. Call this distance f_{eff} . Now,

EXPERIMENT 2

$$\frac{1}{f_{\text{eff}}} = \frac{1}{f_1} + \frac{1}{f_2} \quad \text{or, solving for } f_2, \quad f_2 = \frac{f_1 \times f_{\text{eff}}}{f_1 - f_{\text{eff}}} \quad (5)$$

describes the effective focal length, f_{eff} , of two lenses touching where f_1 and f_2 are the focal lengths of each individual lens. Use this relation to calculate the focal length of the diverging lens. Remember that the focal length of a diverging lens is a negative number. Don't forget to estimate the uncertainty in the lens's focal length.

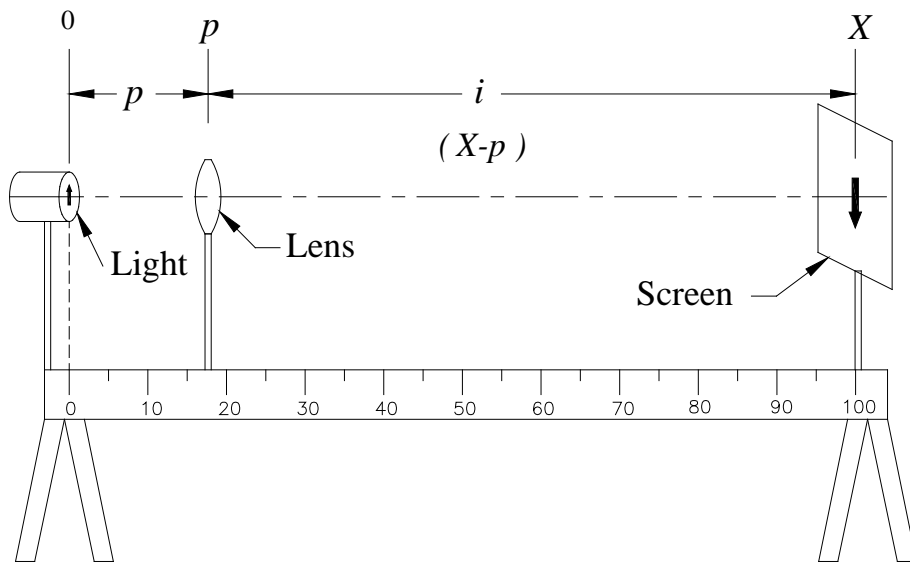


Figure 3 Diagram showing how components should be set up on the optical bench.

Measuring focal length by measuring object and image distance.

3) Return to the laboratory with your equipment. In this part of the experiment you will measure different object and image distances for the converging lens and then calculate the focal length to verify the lens equation. Mount the light source on the optical bench with the object arrow at the zero mark on the bench. See Figure 3. Place the screen at the 100.0 cm mark on the bench and place the medium thick converging lens (#2) at about the 5 cm mark. Adjust the height of the center of the light source, the lens, and the card so that they are all in a straight level line. See Figure 3. This is necessary so that the image formed by the lens stays centered on the screen. **Make sure the screen and lamp are perpendicular to the optical axis of the lens and that the axis of the lens is parallel to the optical bench.** This will minimize aberrations in the image and make it easier to focus. Move the lens away from the light source until an image is formed on the screen. Carefully adjust the position of the lens until the image formed on the screen is the sharpest.

4) Set up a data table with the following columns:

Screen Position	Object Distance	Image Distance	Focal Length
X	p	$i = X - p$	$f = p i / (p + i)$
100.0	35.0	65	22.75

Record the positions X and p in your table. (Figure 3 is drawn to correspond to the data in the above table.) Move the screen about 5cm from its present position toward the light and adjust the lens position until the image is sharpest. Record the new values of X and p in your table. (You need not record i or f in your table; as they will be calculated by Excel.) Also estimate the

EXPERIMENT 2

uncertainty in p as you did in (1). (As the object distance changes, so will your ability to determine the position of best focus. Thus, the uncertainty in p will also change.) Continue moving the screen towards the light source in 5cm increments until the lens no longer forms a sharp image on the screen. When you get to a screen position of 40.0cm use 41.0cm instead. At this point (around 40cm), you will need to move the screen away from the light source to 45cm. Again move the lens **away from the light source** (p should be increasing from before) to form a sharp image on the screen. See Figure 4. Record the position as before. Continue moving the screen away from the light source in 5cm increments and adjust the lens to get the sharpest image. Record data as before until the screen is back at 100.0cm. When you are done, you should have at least 25 data points. If you don't, go back and fill in some extra points until you have a total of 25 measurements.

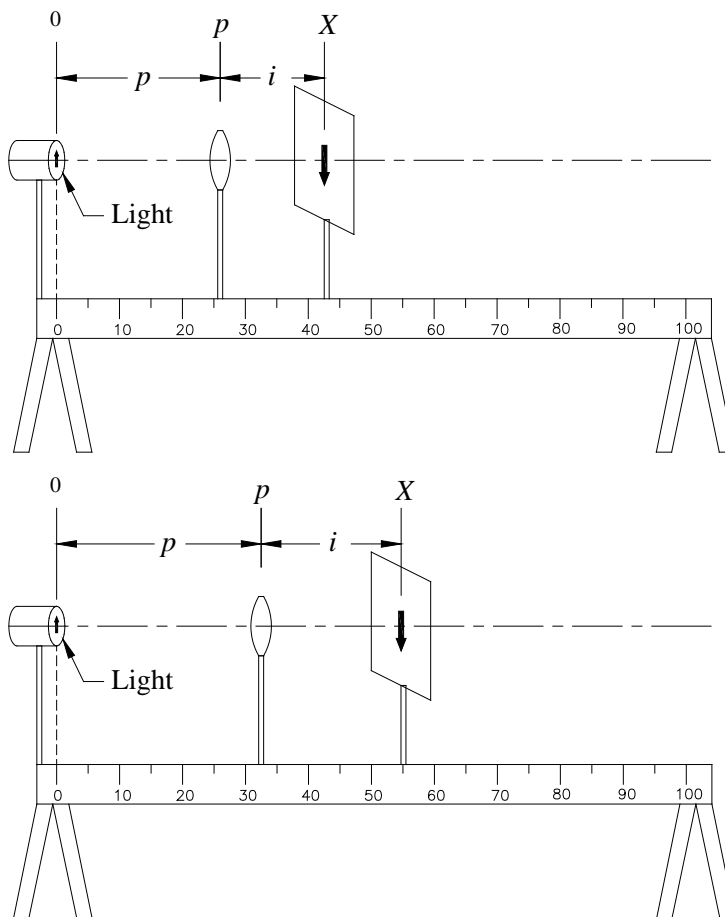


Figure 4 Diagram showing how the lens position should increase as the screen moves to the right.

5) Use the Excel template to calculate the image distance, $i = X - p$, and use i and p to calculate the focal length of the lens by using the thin lens equation solved for f for each point. Keep at least two decimal places in your results. Look at the values for the focal length. You would expect them to all to be equal, but they probably are not. The variation comes from the uncertainty in measuring the object and image distance for each point.

6) To get a feeling for the uncertainty in your calculated focal lengths, calculate the propagated uncertainty in f based on your uncertainties for i and p .

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$$\frac{df}{f} \gg \frac{di}{i} + \frac{dp}{p} \quad (6)$$

7) Use Excel to compute the average focal length, f_{ave} , and the standard deviation, s , for this data set.

Note: In preparation for the next step, you might want to create a column of sorted focal length values (f).

8) Count the number of points, N_s , that are within one standard deviation of the average. (Add s to the average and subtract s from the average. Then count the number of points within this range.) Count the number of points, N_{2s} , that are within two standard deviations of the average. (Add $2s$ to the average; subtract $2s$ from the average, and then count the number in this range.) Compare N_s and N_{2s} with 0.68 and 0.95 times the total number of points respectively. Finally compare $2s$ and s to the \mathcal{G} you found in step 6 and comment.

9) Now after all this analysis, write down what you think is the best value, with uncertainty, for the focal length of this lens. Explain why you quote the values that you do.

10) From your data table, make a graph of p as a function of i . In other words, make a graph with i on the x -axis and p on the y -axis. Looking at Equation 1 and your graph, what are the "asymptotic" limits of this graph?

11) From your data table, make a graph of $1/p$ as a function of $1/i$. Look at Equation 1. What form do you expect for this graph? What intercepts do you expect? Does the graph meet your expectations?

The Power of a Lens

Opticians, optometrists and ophthalmologists speak of the "power" of a lens rather than the focal length of a lens. Power, P , is the inverse of the focal length, i.e. $P = 1/f$. Power is generally measured in **Diopters**. One Diopter is 1m^{-1} .

12) What is the power of the converging lens that you tested? What is the power of the diverging lens? (You don't need to calculate uncertainties for this step.)

13) Let P be the power of a lens, measured in Diopters. Let I and O be respectively the image and object distances expressed in Diopters (i.e. in inverse meters). What will the thin lens equation (Equation 1) look like in terms of P , I and O ?

References

Halliday, Resnick and Walker, *Fundamentals of Physics*, 7th ed., section 34-7 (pages 935-941).

Experiment 3 - Lenses and the Eye

A simple eye model will be used to demonstrate some of the common disorders of the eye that can be corrected with eyeglasses. A simple magnifier, a microscope, and a telescope will be constructed and investigated.

Apparatus

Eye model with lenses and light source, eye chart, optical bench, converging and diverging lens set, large converging lens in holder, blank screen with grid on one side, illuminated object, and centimeter rule.

The Eye

The eye acts as a simple lens system that projects an image of the outside world onto the retina. The image is then converted to nerve impulses by the rod and cone cells which are photo-receptor cells on the surface of the retina. The surface of the *cornea* and a piece of tissue called the *crystalline lens* combine to form the "lens" that makes the image. See Figure 1. In order to provide a clear image on the retina the lens equation, $1/p + 1/i = 1/f$, must be obeyed. Since the image distance is fixed by the diameter of the eye, some means of varying f must be provided for to cope with varying object distances. When the *ciliary muscles* contract, the crystalline lens assumes a more rounded shape corresponding to a shorter focal length lens. This process is called *accommodation*, allows a focused image to be formed on the retina for nearby objects. With age the crystalline lens becomes more rigid, resulting in a loss of accommodation. For this reason, most older people eventually require reading glasses even if they do not need glasses for distance vision. This condition is known as *presbyopia*.

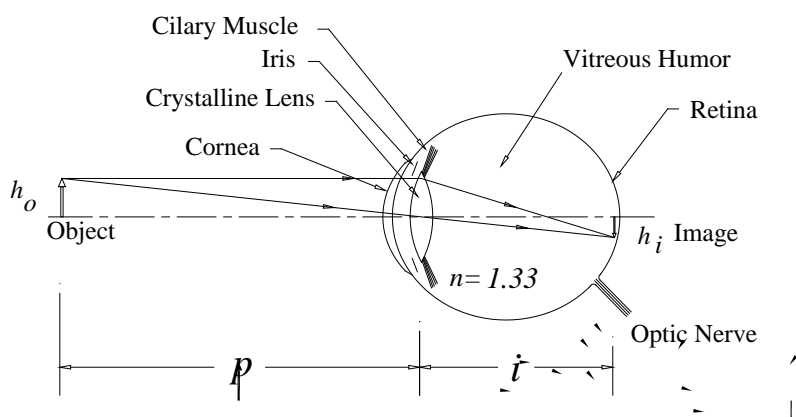


Figure 1 Diagram of the eye showing how images are formed on the retina.

This is a very crude model of the eye. The visual system is actually very complicated and a subject of current research. The retina is not merely a passive screen on which an image is projected. A great deal of image processing is done by the visual system, beginning at the level of the retinal cells. For example, hold your arms out to the side at shoulder level and slightly forward. Now wiggle your fingers and then stop. If you have your hands in the right place the fingers will disappear when they are not moving. This is because the cells at the periphery of the retina are most sensitive to motion. As another example, there are NO receptor cells where the optic nerve

EXPERIMENT 3

connects to the retina. Any part of the image falling on this area of the retina is lost. The visual system smoothes this over, so that you are not conscious of any "holes" in your visual field.

The spacing and distribution of rod and cone cells on the retina is not uniform. Only in a small central area of the retina known as the *fovea* are they close enough to resolve fine detail. If two points on the image are closer together than the spacing between receptor cells they will not be resolved. **The minimum angular separation of objects resolved by the eye is approximately one minute of arc which is 1/60 of a degree.**

The eye, like any organ of the body, can develop defects. The most common defects of the eye's optical system are *myopia* (near-sightedness) and *hyperopia* (far-sightedness). In myopia the lens is too powerful for the length of the eye and the image forms in front of the retina. By the time that the light rays reach the retina they have begun to diverge and the resulting image is a blur. This condition is corrected by placing a diverging (negative focal length) lens in front of the eye. The power of the lens is such that the combination of eye plus diverging lens has the correct focal length to form an image on the retina. Hyperopia is the opposite problem: the lens of the eye is too weak for the length of the eye and the image forms in back of the retina. This condition is corrected by placing a converging lens in front of the eye. Again, the resulting combination of eye plus converging lens has the correct focal length to form an image on the retina.

1) Observe your blind spot by the following method. Cover your right eye with your hand and look directly at the **X** below with your left eye. Vary the distance of the page from your eye while looking directly at the **X**. When the image of the image of the **O** falls on top of your blind spot the **O** will disappear!

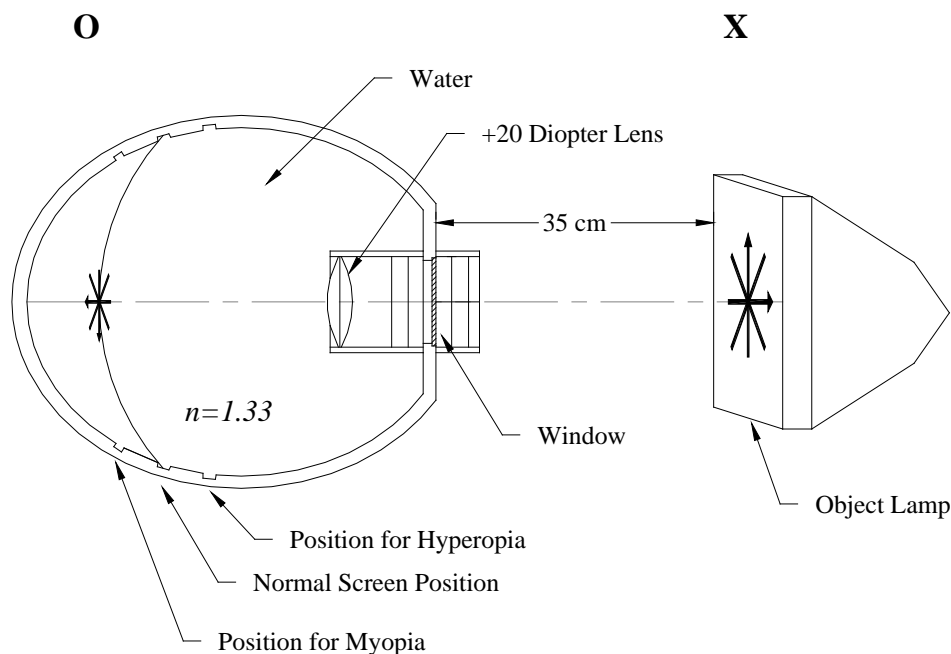


Figure 2 Diagram showing how to setup the eye model.

2) Working with the Ingersoll eye model. Figure 2 is a diagram of the eye model with which you will experiment. The model is first filled with distilled water to within about 2 cm. of the top. This is to simulate the vitreous humor of the eye. The movable screen represents the retina. A small black box contains the lenses to be used with the eye model. Find the +20 Diopter lens and place it in the slot closest to the retina. This simulates the crystalline lens. Move the screen in the eye model, which represents the retina, to the center (normal) position. The illuminated object should

EXPERIMENT 3

be set about a third of a meter away from the model. Adjust the position of the illuminated object until a clear image is obtained on the retina. Now move the retina in the eye model to the position farthest from the crystalline lens. Observe and record the appearance of the image. This represents myopia or "near sightedness" since the image is now formed in front of the retina. This condition can be corrected by placing either a (+2.00D) or a (-1.75D) lens in front of the eye. The model is now wearing glasses. Which lens works? Is it a converging or diverging lens? Repeat the procedure with the retina in the near position (representing hyperopia). Which lens corrects the condition?

3) In your lab report, make qualitative ray drawings for the myopic and hyperopic cases both with and without the correcting lens. The ray drawings with and without the corrective lens should be drawn to the **same scale** and clearly show how the light rays focus on or off the retina.

4) The Snellen Eye Chart. Measure the height (in centimeters or millimeters) of the **E** on the 20/200 line of the Snellen eye chart. Assuming that the viewer's eye is 200 feet from the chart, what angle is subtended by the entire **E** at the viewer's eye? Express the angle in radians and also in minutes of arc. (One minute of arc is 1/60 of a degree.) When doing your calculations, don't mix units; be sure to use all metric units of measure or all English units of measure.

5) Measure the thickness of the upper horizontal bar of the **E** on the 20/200 line of the chart. (This thickness is considerably less than the height of the entire **E**.) Assuming again that the viewer's eye is 200 feet from the chart, what angle is subtended by this horizontal bar at the viewer's eye. Express the angle in minutes of arc.

6) Question: Are the angles that you calculated consistent with the earlier statement that the "minimum angular separation of objects resolved by the eye is approximately one minute of arc"?

Measure the Focal Length of Lenses

7) Measure the focal length of the three converging lenses in the Plexiglas lens set before doing any of the following parts.

To determine the focal length of the lenses take the optical bench, lens set, lens holder, and screen out to the walkway overlooking the "Focus" area as you did in the last lab. Again, place the bench on the floor and image the windows at the far end of the building with each lens onto the screen. Recall that if the object distance is infinity, the image distance is equal to the focal length of the lens. Measure and record the focal length of all three converging lenses in your set. Also notice the difference in the images formed by each lens.

8) Questions: Report your results in a table.

Which lens produces the largest image?

Which the smallest?

Which lens makes the brightest image?

Which makes the faintest image?

EXPERIMENT 3

Magnification

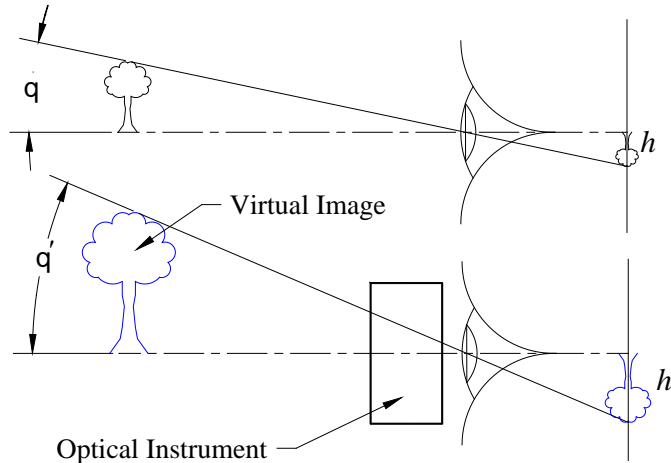


Figure 3 Generalized optical instrument.

In today's lab you will be looking through an optical instrument that produces a virtual image of the object you are viewing. When you view the object unaided it appears to have an angular size of q . When you view it through the instrument, the size of the virtual image is q' . The magnification M_q is the ratio of these two angles

$$M_q = \frac{q'}{q}$$

From Figure 3 you should see that the path of the central ray determines the size of the image formed on the retina.

The Simple Magnifier

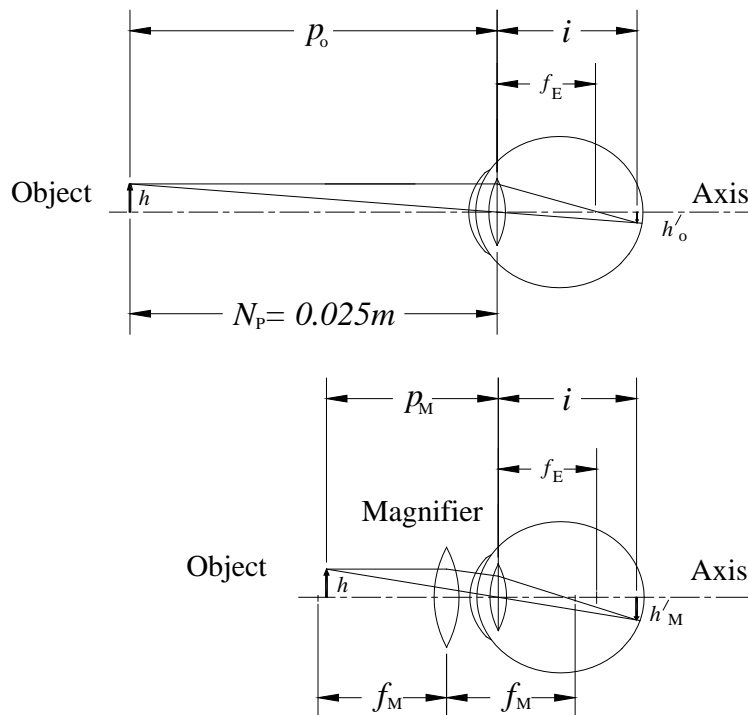


Figure 4 Ray tracing showing how a simple magnifier works.

EXPERIMENT 3

For a simple lens the size of the image relative to the size of the object, h_i/h_o , is given by the ratio of the image distance to the object distance, i/p . For a fixed image distance, as you have with the human eye, you can increase the size of the image by reducing the object distance. (The closer you get to an object the bigger it gets.) The amount of accommodation of the eye limits the minimum object distance. For a clear image the lens equation must be obeyed, $1/p + 1/i = 1/f$. Since the diameter of the eye is constant, a smaller object distance requires a shorter focal length lens. You can decrease the focal length of your eye by use of your ciliary muscles, but only to a limited extent. Beyond this point you need outside help, in the form of a converging lens inserted just in front of the eye. The combination of eye plus magnifying glass gives your eye a shorter effective focal length. The effective focal length of the combination is where the parallel ray from the object crosses the optical axis of the eye, see Figure 4.

The magnification, M , of the magnifying glass is given by the ratio of the size of the image on your retina with the magnifier, h'_M to the size of the image without it, h'_o . From the top part of Figure 4 you should see that $h'_o = i/p_o$. From the bottom of Figure 4 you can see that $h'_M = i/p_M \gg i/f_M$. When you take the ratio of h'_M / h'_o the i 's drop out and the magnification becomes,

$$M = \frac{p_o}{f_M}.$$

The above definition is somewhat ambiguous, since the size of the image in both cases depends on how hard your eye is working. Bringing the object closer while still keeping it focused makes your eye work harder. The **near point**, N_p , is the smallest distance that an object can be to your eye and still be clearly focused. In general, if you wanted to investigate an object in detail, you would move it to your near point. The magnification is then,

$$M = \frac{N_p}{f_M} \quad (1)$$

where N_p is the near point, and f_M is the focal length of the magnifier. In most texts you will find this formula with a 25 instead of N_p and an admonition to use f_M in cm. This is due to the convention that all magnifying powers are estimated with a N_p of 25 cm to provide a standard for comparison. To make the measurements easier in this lab, you will use the actual near point (the distance from the object to your eye) and not the ideal 25cm.

EXPERIMENT 3

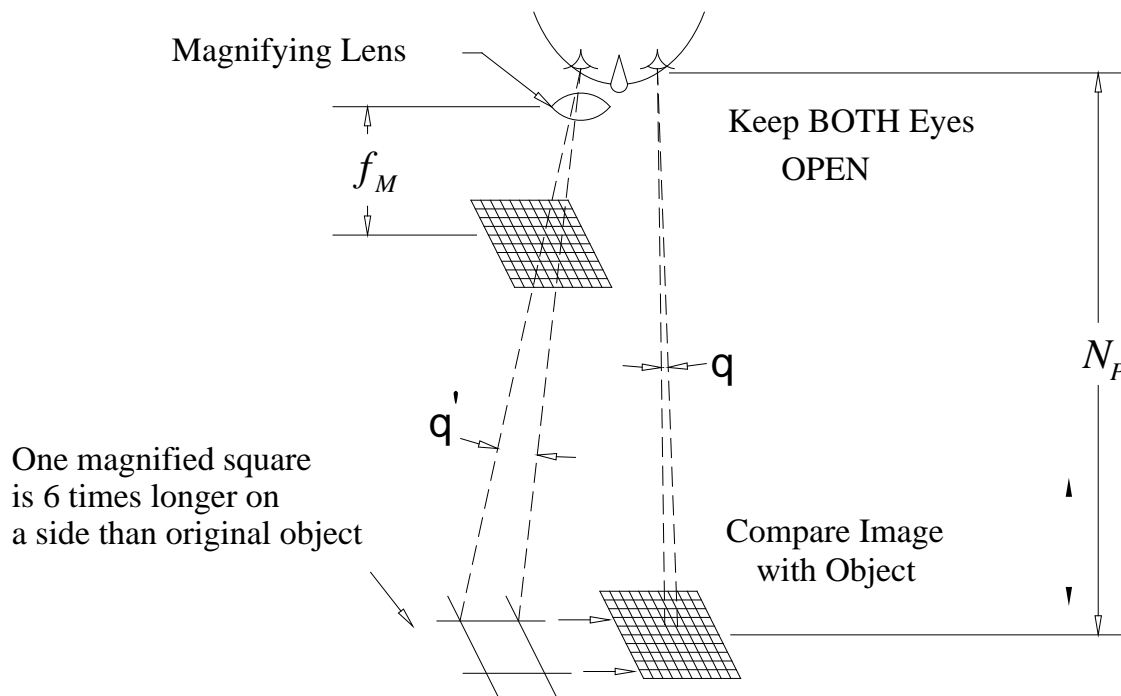


Figure 5 Diagram showing how you can estimate magnification using two grid charts.

9) Estimate the magnifying power of the medium focal length lens by the following method. Find the two small cards printed with a 5cm x 5cm millimeter ruled grid. Place one of the cards on the lab table. Move your head over the paper so that you can comfortably focus on the grid. Now **keeping both eyes open** place the magnifying lens in front of your right eye and as close to it as possible. Take the other card and place it in front of the magnifier. Move the card until a sharp image is formed with the magnifier. See Figure 5. Now the tricky part. Keeping both eyes open compare the two images, estimating how much taller one of the squares in the magnifier is compared to the grid viewed without. Write a sentence or two describing what you see or make a simple diagram. If you have trouble using both eyes together try blinking to look first though one eye and then the other. (Additionally if you have trouble doing this try putting the lens over your left eye. You may be left eye dominate. Ask your lab instructor how to determine which "eyed" you are.) To help in your estimate, every tenth line is ruled wide. Have your lab partner measure the distance from your eye to the lab table where the card is laying. This will be the value of the near point to use in calculating the magnification.

10) Calculate the magnification, $M = N_p/f_M$ using the distance between your eye and the screen on the table for N_p . How well does your estimated magnification agree with this?

The Compound Microscope

By using a combination of two lenses a compound microscope can be constructed which has much greater magnifications can be obtained than with a single lens. The first lens is called the **objective** and typically has a short focal length. The object is placed very close to the focal point, f_o , so that an enlarged inverted image is produced. See Figure 6. The magnification, h_i/h_o , due to the objective is found from the ratio of the image distance to the object distance, i/p . This image can be magnified further by using a simple magnifier, which is called the **eyepiece** and has a focal length f_e . See Figure 7. The magnification of the eyepiece is given by the ratio of image to object distance, i'/p' . The placement of the eyepiece is important to get a sharply focused image. This happens when the object distance to the eyepiece is approximately equal to its focal length. In a

EXPERIMENT 3

typical set up the image distance of the first lens, i , is equal to the difference of distance between the lenses, L , and the focal length of the eyepiece, f_e . The object distance to the first lens is approximately the focal length of the lens, f_o . For the second lens the object distance, p' is almost equal to the focal length of the magnifying lens, f_e . The new image distance, i' is simply the distance at which the image from the objective is viewed, which is the near point, N_p . The total magnification of the microscope is the product of the magnifications from each lens:

$$M = \frac{(L - f_e)}{f_o} \times \frac{N_p}{f_e} \quad (2)$$

11) Mount the short focal length lens at about the 6 cm point on the optical bench. Mount the crossed arrow light source at 0 cm, and the white viewing screen at 35cm. See Figure 6.

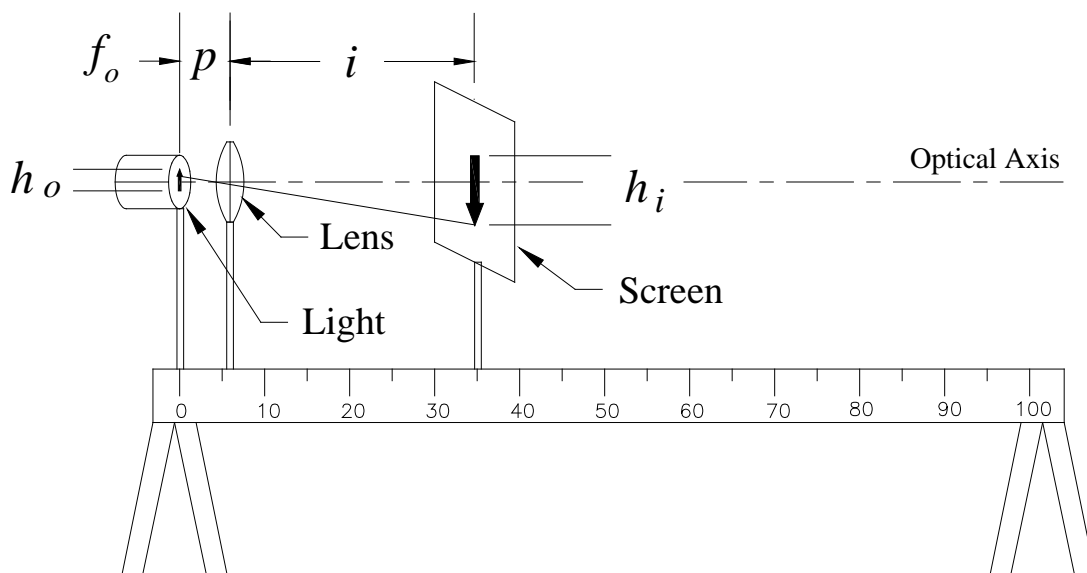


Figure 6 Diagram showing the first step in the construction of a microscope.

12) Move the lens until you get as clear an image as you can. Adjust the height of the lens to center the image along the optical axis. This image should be about 6 times larger than the object. Record the object and image distance. This is the image from, the objective that will be viewed with the simple magnifier.

13) Now replace the illuminated source with the screen grid target making sure you do not move the position of the mount. You want to keep the object distance the same so that the magnification stays the same as with the illuminated source. Position the medium focal length lens a distance approximately equal to its focal length away from the where the screen was in step 12. This lens is the eyepiece. See Figure 7. Look through the eyepiece at the object. You will need to place your eye at the *exit pupil* so that as you look through the lens the image completely fills the field of view of the eyepiece. The exit pupil is formed where the eyepiece creates an image of the objective lens. In this case it should be about 10 to 12cm behind the eyepiece. Once you have your eye positioned correctly move the eyepiece closer or farther from the objective lens until the image is in focus. Note that the position of the light source and the screen holder might be a millimeter or so different. If this is the case you will need to move the objective lens slightly to get the best focus. Estimate the magnification as you did with the simple magnifier, by comparing the unmagnified

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object with the image in the microscope. To make this comparison easier, you should align the two images by adjusting the height of the eyepiece in its holder.

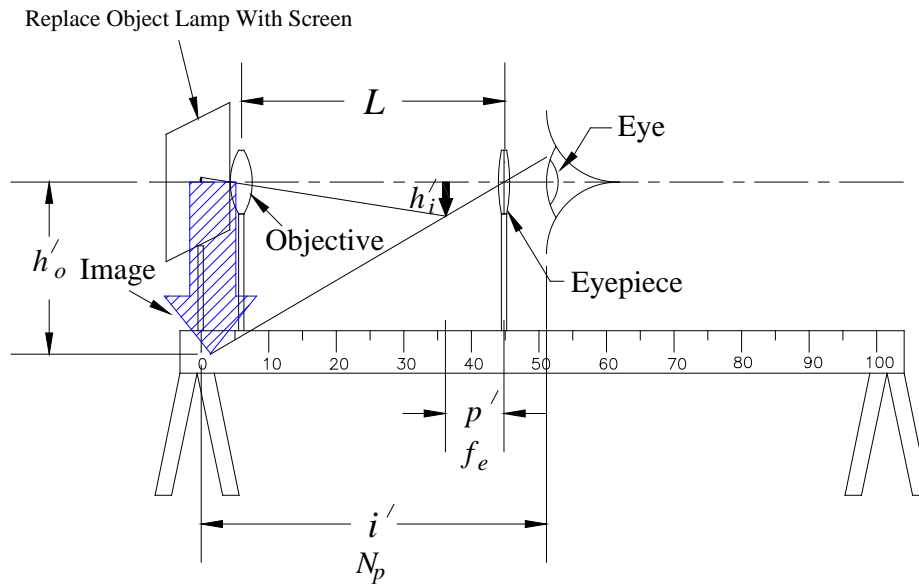


Figure 7 Diagram showing the second step in constructing a microscope.

14) Measure L , the distance between the lenses, and N_p , the distance from your eye to the comparison object. Then, using your measured values for the focal length of the lenses, compute the microscope's theoretical magnifying power using Eq.(2). Compare your theoretical value with your estimated value. Does the theoretical magnification seem like a reasonable value?

EXPERIMENT 3

The Astronomical Telescope

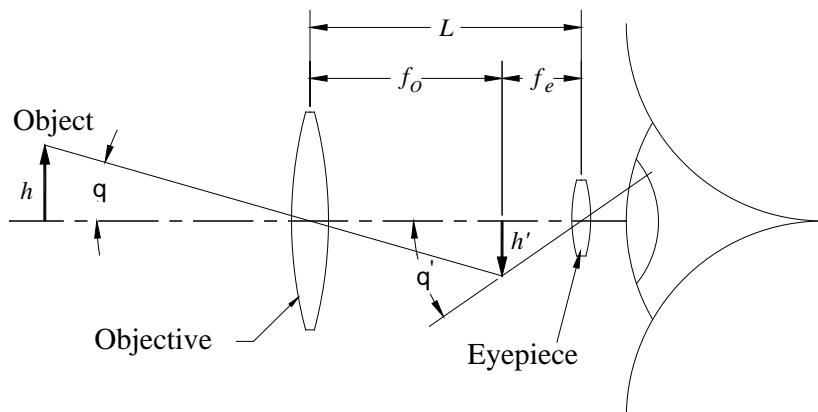


Figure 8 Central ray diagram for an astronomical telescope.

An astronomical telescope consists of an objective lens of long focal length, f_o , and an eyepiece lens of short focal length, f_e ($f_e \ll f_o$). The lenses are placed a distance approximately equal to the sum of their focal lengths apart. The object is assumed to be far enough away from the telescope that the bundle of light rays leaving a given point on the object and entering the telescope may be considered to be parallel (i.e., $d_o \gg$ infinity). Since the rays are parallel we will only consider the ray leaving the tip of the object passing through the center of the lens and then forming an image at f_o . See Figure 8. This is the central ray. Since the image point is at the focus of the eyepiece the bundle of rays emerging from the eyepiece will also be parallel. To find the magnification, look at the ray leaving the tip of the arrow at an angle of q with the optical axis. After passing through the telescope and exiting the eyepiece the angle has increased to q' . The apparent size of the object is determined by the angle q' , so that the object appears larger by a factor of $M = q'/q$. For small angles

$$M \gg \frac{f_o}{f_e} M$$

15) Take your optical bench with the large double-convex lens and the lens set back out on the walkway over the "Focus" area and observe objects out the window at the far end of the building. Measure the focal length of the large double-convex lens as you had previously. Remove the screen from the bench.

16) Mount both lenses on the optical bench with the eyepiece near one end of the bench and separated by a distance approximately equal to the sum of their focal lengths, $L = f_o + f_e$.

17) Look through the telescope at a distant object and move the eyepiece lens slightly to get the **best** focus. As with the microscope it is necessary to place your eye at the exit pupil which is a spot formed by the eyepiece making an image of the objective. For the medium focal length lens used as an eyepiece this distance will be about 12cm and for the short focal length lens it will be about 6cm. Describe the view you see through this instrument.

18) Calculate the theoretical magnification, $M = f_o/f_e$. Estimate the magnification by comparing the unmagnified object with the virtual image in the telescope. Describe what you observed to make this estimate. Does the theoretical magnification seem like a reasonable estimate of the magnification?

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Newtonian Telescope

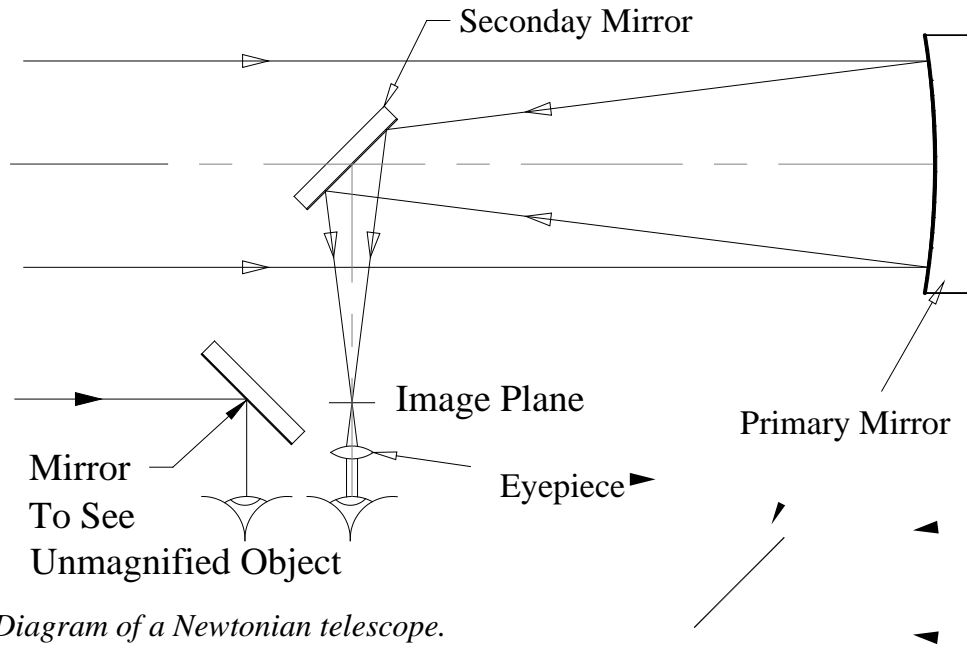


Figure 9 Diagram of a Newtonian telescope.

19) Look through the Newtonian telescope if your instructor sets it up. How does the quality of the image compare to the astronomical telescope you built with lenses.

20) Estimate the magnification and compare it to the theoretical value, $M = f_o/f_e$.

References

Hecht, *Optics*, 3rd ed., Sections 5.7.1 and 5.7.2 (pages 203 to 212)

Halliday, Resnick and Walker, *Fundamentals of Physics*, 7th ed., section 34-8 (pages 941-944).

Experiment 4 - Interference and Diffraction

In this lab, you will study how waves from two light sources combine to form interference patterns. A red Helium-Neon laser will be used to illuminate assorted slit pairs. The pattern will be projected onto a screen which has a millimeter scale. The spacing between the slits will be determined by making measurements of the interference pattern. You will also investigate diffraction effects as light passes through or around small objects. The width of a slit and the diameter of a wire will be found by making measurements of the distance between intensity minima in the diffraction pattern. The thickness of a very thin object will be found by counting interference fringes formed between two glass plates with a green mercury lamp.

Apparatus:

He-Ne laser, millimeter screen, multiple slit plates, single slit plates, thin wire in holder, meter sticks, plate holder with stand, glass plates with hair, and a green Unilamp®.

Double Slit Interference

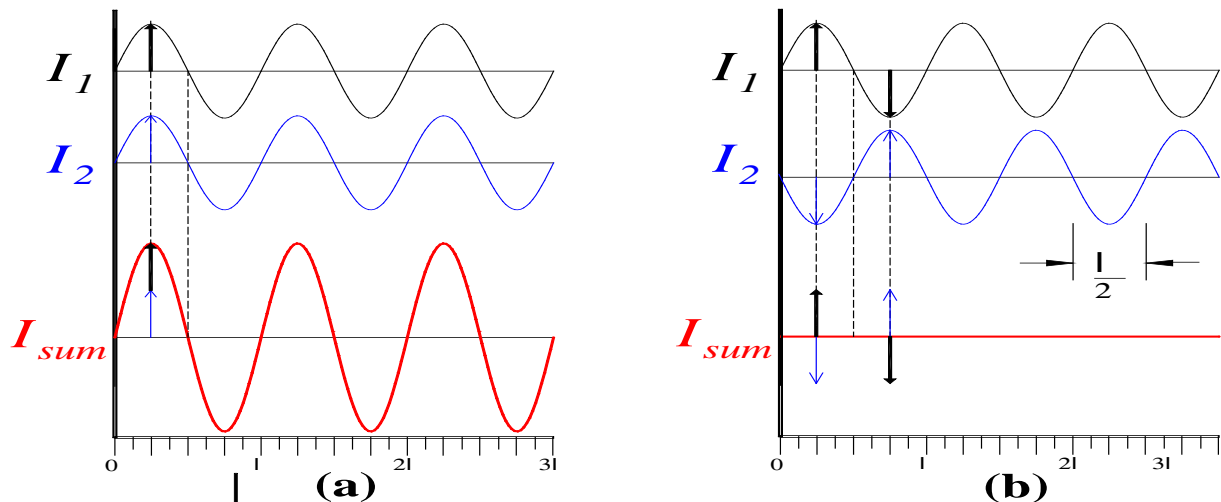


Figure 1 (a.) Graph showing how two sine waves in phase add for constructive interference. (b.) Graph showing how two sine waves 180° out of phase cancel for destructive interference.

Many physical phenomena are best described in terms of wave, or oscillatory, motion. In the case of light or sound, the actual motion of the waves is not "visible". In the case of water waves, the motion of the waves can be seen. If you have ever watched boat wakes on a river or lake, you have probably observed how waves traveling in different directions pass through each other without affecting the motion of each other. As the waves pass through each other, the observed amplitude of the wave pattern is a result of the sum (i.e., the superposition) of the many waves that are combining. At some point two waves can form a huge wave and just a moment later the amplitude of the wave at the same point can be zero. When two equal amplitude waves are exactly "in phase", their amplitudes add to form a wave which is double in amplitude. This is called **constructive interference** as shown in Figure 1(a) When two equal amplitude waves are 180° "out of phase", the resulting amplitude is zero. This is called **destructive interference** and is shown in Figure 1(b) Two waves that start out in phase can be made out of phase if one wave travels a distance one-half wavelength ($\lambda/2$) greater than the other. When these waves combine, destructive interference will result. The summing of different wave amplitudes by **superposition** is what gives rise to the diffraction and interference patterns that you will be studying today.

EXPERIMENT 4

If coherent light passes through two closely spaced apertures and is then allowed to combine, a double-slit interference pattern will be observed on a screen as shown in Figure 2. From this pattern the angle q where the intensity pattern is a MAXIMUM can be determined. Call the distance between the centers of the two slits d . Let the distances from the center of the slits to the screen be r_1 and r_2 respectively. The location of the first maximum will occur when the difference in distances ($r_1 - r_2$) is equal to one wavelength (λ). This puts the waves back "in phase." Looking at Figure 2, you should observe that the small triangle in front of the slit (with hypotenuse d and side λ) is approximately similar to the large triangle (sides L and y). From this, you can see that $\sin q = \lambda / d$. The next (or *second order*) maximum will happen when the difference in distance is 2λ . The *interference equation* relates the wavelength to the location of the maxima :

$$m \lambda = d \sin q \quad \text{where } m = 0, \pm 1, \pm 2, \dots \quad (1)$$

In this equation, d is the separation between the slits, m is the order of the maximum, λ is the wavelength, and q is the angle.

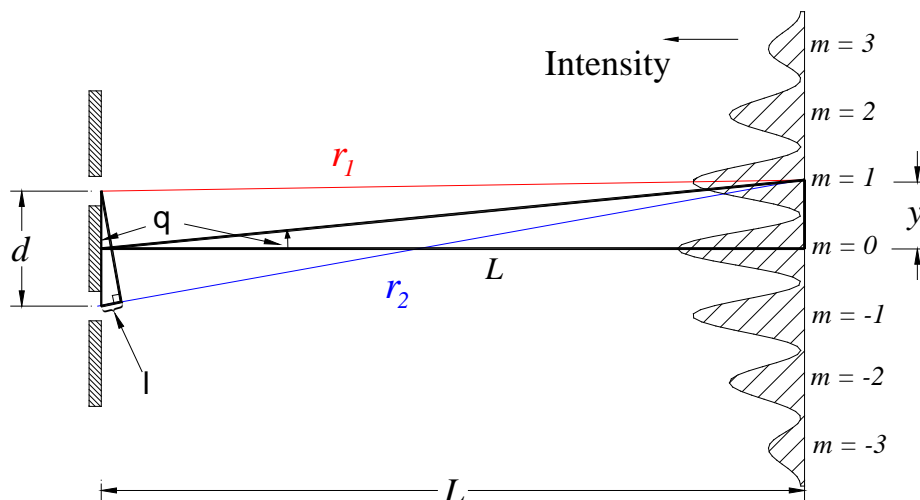


Figure 2 Diagram showing how different ray paths combine to form an intensity pattern on a screen.

You will be using a Helium-Neon laser as a *monochromatic* (one color) light source. **The wavelength of the light from the laser is $\lambda = 632.8\text{nm} = 0.6328\text{mm}$.**

REMEMBER: DO NOT LOOK INTO THE LASER BEAM.
BE CAREFUL NOT TO LET REFLECTIONS ENTER YOUR EYE.

In this part of the experiment you will illuminate a double slit with a laser and allow the interference pattern to form on a screen with a calibrated scale. You will first look at two slit-pairs that differ only in the separation between the slits. You will then make measurements to determine the separation between the slits for each pair.

1) Set up your components as indicated in Figure 3. Adjust the distance between the slit holder and the screen to be approximately 2.0 meters. Also place the slit about 10 to 20cm away from the laser, this will allow the laser beam to expand slightly to illuminate both slits. Turn on your laser. The slit-pairs are labeled from A to D at the top of the slide. Look closely because the slits are very small. Move the slit holder so the beam of the laser illuminates slit pattern A. Watch the screen; you should see a horizontally spread out line of red light that has a series of bright "dots" about 3mm tall by 4mm wide. These "dots" are the interference intensity peaks (the maxima) you are trying to measure. Ever so

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slightly, adjust the slit holder perpendicular to the laser beam until the "dots" on the screen are as sharp as possible. The slit-pair will now be centered in the beam. Notice how the spacing between the "dots", or maxima, is constant. Roughly measure the distance between the centers of two adjacent maxima.

2) Repeat the above measurements for pattern B. In this case the "dots" will look more like fine vertical lines when the slit is properly positioned. Also observe what changes in the pattern as you change the slits from A to B.

3) QUESTION - According to your observations, what happens to the spacing between maxima formed on the screen as the separation between the slits increases? Is this what is predicted by Eq. 1?

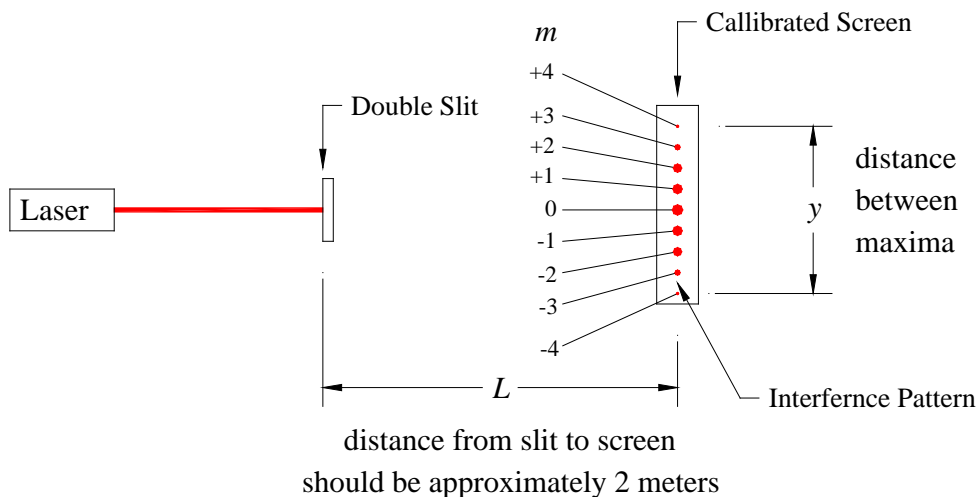


Figure 3 Diagram showing setup for viewing double slit interference. For the y above, Δn is 8.

4) Since the angles between maxima are small, the **small angle approximation** $\tan \theta \approx \sin \theta \approx y/L$ can be used, where y is the distance between maxima and L is the distance from the slit to the screen. Since the angles are small the separation between maxima is constant, which allows us to measure across the central maximum when determining the angle θ . If Δn is the change in the number of maxima, then the distance d between the slits can be found from

$$d = \frac{\Delta n \lambda}{\sin \theta} = \frac{\Delta n \lambda L}{y} \quad (2)$$

5) Return slit pattern A into the beam and optimize its position as you did before. Measure and record the distance L from the slit-pair to the screen. To get the best value for the slit width, choose as large a change in the number of maxima to measure over. Count and record the change in maxima, Δn . Measure and record the distance spanned by these maxima, y . See Figures 3 and 4. Use Eq. 2 to calculate the separation between the slits, d . Estimate the absolute uncertainty in your value for the slit separation. (You should use the method of addition of fractional uncertainties to find the uncertainty in the slit width.)

6) Repeat step 5 to determine the distance between slits d for slit pattern B.

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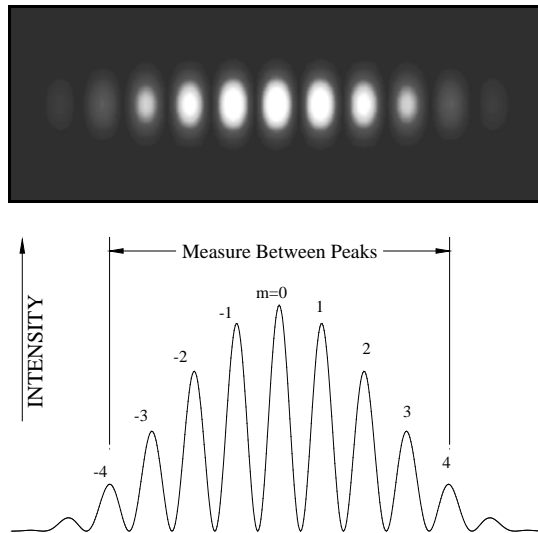


Figure 4 (top) Picture of the double slit interference pattern for slit A. (bottom) Intensity plot of the double slit pattern for slit A ($D\lambda$ for this measurement is 8.)

Single Source Diffraction

When a wave front passes through an aperture or passes around a small obstacle, some of the rays in the wave front are "bent" from a straight line. When several of these bent rays then recombine by superposition, a diffraction pattern is formed. In this part of the experiment, you will investigate the diffraction pattern formed as light interacts with small apertures and objects. For simplicity you will be investigating only the diffraction pattern formed at very large distances from the objects.

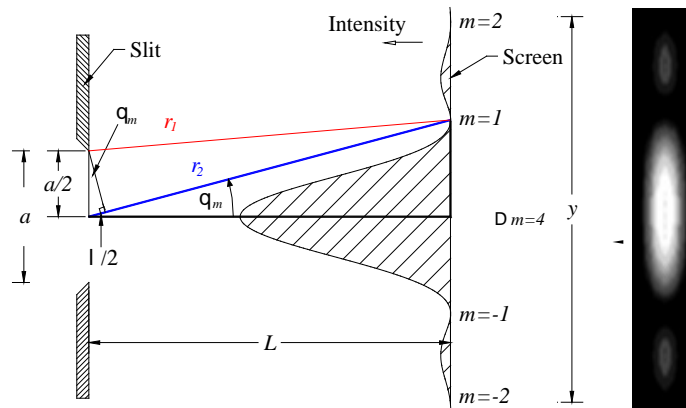


Figure 5 Diagram showing how a ray from the edge of the slit combines with a ray from the center to form an intensity minimum on the screen. On the right is a picture of an actual diffraction pattern projected at the same scale as the intensity plot shown on the left.

One way to understand what happens when light passes through a small aperture is to imagine a ray r_1 of light that starts at the edge of an aperture of width a and a ray r_2 that starts at the middle of the aperture. Both rays end up combining to form an intensity pattern on a screen that is a distance L from the aperture as shown in Figure 5. At some angle, q_m , the distance to the screen for the ray traveling from the middle of the aperture will be half a wavelength longer than the distance traveled by a ray coming from the edge of the aperture. When these two rays combine, the resulting amplitude will be zero. This results in a minimum in the intensity pattern and is called the $m = 1$ or first minimum. If you increase the angle further, the second minimum (or $m=2$) will occur when the difference in path lengths is $3\lambda/2$. In general, the angle q_m where the MINIMA should occur (for single slit diffraction) is given by:

EXPERIMENT 4

$$m \lambda = a \sin \theta_m \quad \text{where} \quad m = \pm 1, \pm 2, \pm 3, \dots \quad (3)$$

Answer the following two questions in terms of Equation 3:

7) QUESTION: If the wavelength (λ) of the waves were to decrease, would the angle of the first minimum get larger or smaller?

8) QUESTION: What would happen to the angle θ_m if the aperture a were decreased?

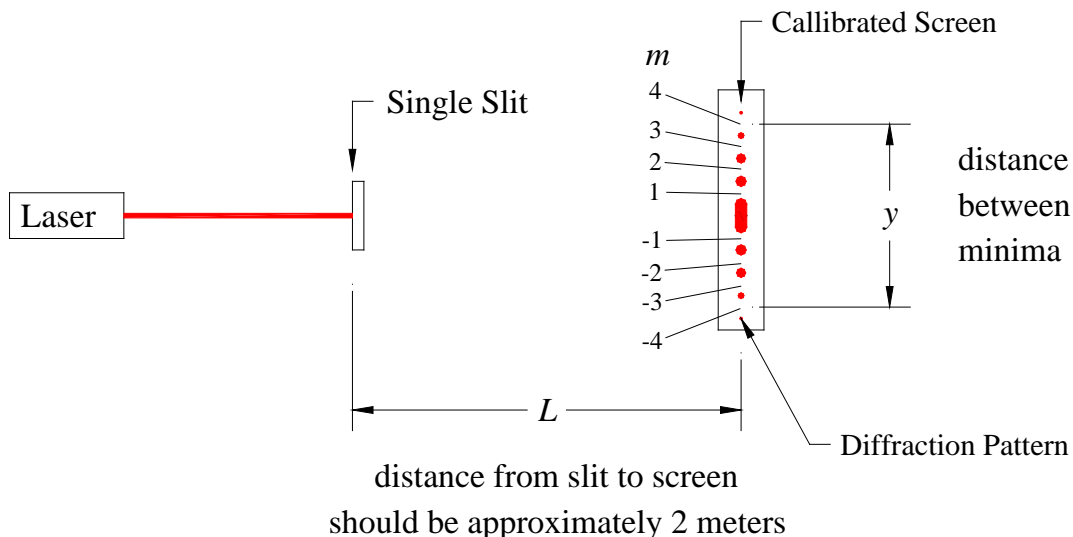


Figure 6 Diagram showing how to observe a single slit diffraction pattern. Notice Δm is 8 for the distance y that is shown.

9) Set up your laser and single slit as shown in Figure 6. Adjust the distance between the slit and the calibrated screen to be approximately 2 meters. Move the slide holder so that slit A is illuminated by the beam of the laser. (The slits are very small and are labeled A to D at the top of the slide.) The diffraction pattern should have a central maximum about 8 to 10 cm wide. Watch the screen and make slight adjustments to the position of the slit until the pattern on the screen is as sharp as possible. Make a rough sketch of the intensity pattern you observe on the screen.

10) Repeat the above observations for the remaining slits (B to D). Try to keep your sketches all to the same scale. Then rank the slits from the brightest central maximum to the faintest and from the widest spacing between minima to the narrowest.

11) Put slit B back into position as you did above.

12) In general, the diffraction minima will be equally spaced except as you go across the central maximum, which is twice the width of the others. Since the angles between minima are small, the substitution $\sin \theta \approx \tan \theta = y/L$ can be made, where y is the distance between minima and L is the distance from the slit to the screen. If Δm is the change in the number of minima, then the width of the aperture a can be found by:

$$a = \frac{\Delta m \lambda}{\sin \theta} = \frac{\Delta m \lambda L}{y} \quad (4)$$

Remember $\Delta m = m_{\text{final}} - m_{\text{initial}}$. So, in Figure 6 Δm is 8 for the distance y between the $m = +4$ and the $m = -4$ minima. Make and record measurements to determine the width of slit B to as high a degree of

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precision as possible. This can be accomplished by counting between the largest number of minima possible and by adjusting the distance between the slit and the screen so that the pattern is as spread out as possible. Estimate the absolute uncertainty in the slit width by the method of adding fractional uncertainties.

13) Remove the slit holder and place the fine wire into the beam of the laser. Observe the pattern formed on the screen.

14) Compare this pattern to the one formed by slit pattern D and comment in your report.

15) Determine the diameter of the wire by the same method you used in step 12) above to measure the width of the single slit. Adjust your setup and make measurements to obtain the best value for the diameter of the wire as possible.

Interference from Multiple Reflections

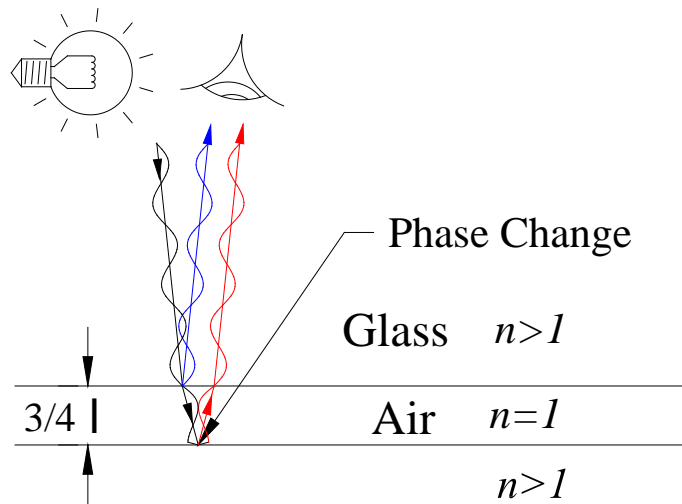


Figure 7 Diagram showing how rays constructively interfere to form a bright fringe. Note that the top and bottom surfaces of the glass are omitted to simplify the drawing.

16) Figure 7 shows the surfaces of two glass plates separated by a small distance d . Consider two monochromatic light rays that pass through the top plate, one bounces off the bottom of the top plate and the other continues on through and reflects off the top of the bottom plate. Both of these reflected rays combine to add by superposition and are viewed by your eye. If the separation between the plates is zero the two combining rays will destructively interfere and a dark fringe will be seen. As you studied in class, when light is reflected from a surface having a higher index of refraction there is a 180° phase shift (π). When light is reflected from a surface having a lower index of refraction there is no phase shift. You can remember this by the following rhyme:

*From high to low no,
from low to high add pi.*

If the separation of the plates increases to $\lambda/4$ then rays will combine constructively and a bright fringe will be seen. If the distance is increased to $\lambda/2$ the rays will again combine destructively and a dark fringe will be seen.

EXPERIMENT 4

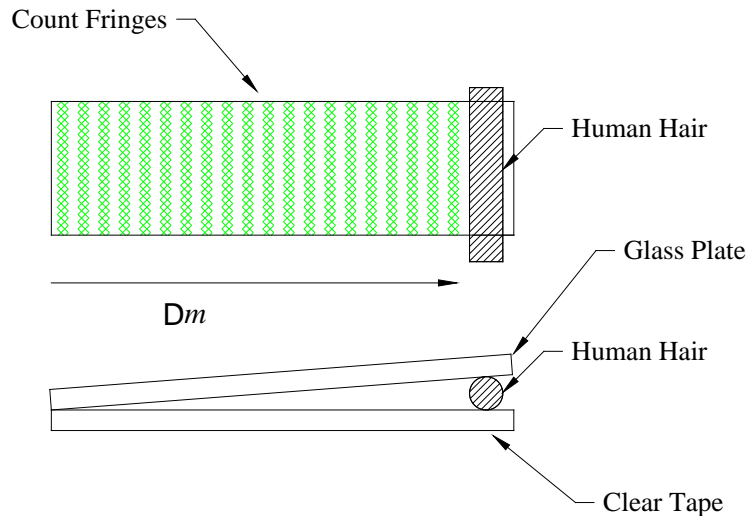


Figure 8 Drawing of fringes formed by two glass plates with a human hair sandwiched at one end. Note that the scale of the hair has been greatly exaggerated.

The thickness t of the material is given by:

$$t = \frac{Dm \lambda}{2} \quad (5)$$

where Dm is the change in number of dark fringes and λ is the wavelength of light.

The green light from a Mercury lamp has a wavelength of $\lambda = 546\text{nm}$. ($1\text{nm} = 10^{-9}\text{m}$)

17) Place the glass plates underneath the green Mercury lamp. Position the plates so that you can observe a reflection of the lamp in the surface of the glass. You should be able to see a series of dark bands running across the plates as shown in Figure 8. Sometimes the fringes are not perfectly straight. Explain what might be wrong.

18) A human hair has been placed in one end of the glass plates. Count the number of dark fringes across the plate and estimate the thickness of the hair along with the uncertainty in the thickness.

References

Haliday, Resnick, and Walker, *Fundamentals of Physics 7th Ed*, Chapters 35 & 36 Sections 1-7. (Pages 958-1004)

Serway, *Physics for Scientists and Engineers with Modern Physics 4th Ed*, Chapter 37.1-37.6 Interference. Chapter 38.1-38.3. Diffraction. About the same level as above, but very good illustrations.

Jenkins and White, *Fundamentals of Optics 3rd Ed*. Chapters 13-18. A very detailed discussion of diffraction and interference.

EXPERIMENT 4

Experiment 5 - Elementary DC Circuits

In this lab, you will build electrical circuits using resistors, batteries, power supplies, fuses, and wires. You will then learn how to use ammeters and voltmeters to measure current and voltage in a circuit. You will test Ohm's Law, and investigate resistors in series and in parallel to find equivalent resistances. Finally, a circuit will be built that will demonstrate Kirchhoff's Voltage Law (or Loop Theorem.)

Apparatus:

Digital multimeter (DMM), resistors, Plexiglas component holders, Lambda DC power supply, AA batteries, fuse block, and banana leads.

Introduction:

A circuit is a set of wires and components through which current flows. A conductor in which energy is dissipated as current flows through it is called a *resistor*. The resistance, R , of a resistor is given in terms of the voltage V across it, and the current i through it, by Ohm's law:

$$R = \frac{V}{i} \quad (1)$$

Resistance is measured in Ohms (Ω), where 1 Ohm = 1 Volt / 1 Ampere.

By convention the direction of current in a circuit is defined as the direction in which positive charges flow. Current flows from the positive terminal of a battery or power supply to the negative terminal. Conventionally the positive terminal of a voltage source or meter is colored red and the negative terminal is black; therefore the current will flow from the red terminal to the black terminal.

Kirchhoff's voltage law states that the sum of the voltage (potential differences) around a circuit is equal to zero. Mathematically this can be written as:

$$V_1 + V_2 + V_3 + \dots + V_n = \sum V_i = 0 \quad (2)$$

where the V_i 's are the voltage drops or gains across each component in the circuit.

The Digital Multimeter

The *digital multimeter* is an instrument capable of measuring current, voltage, and resistance. For the types of circuits we will be using in this lab it is an "ideal" instrument, i.e. it does not disrupt the circuit.

Make sure the meter is not connected to a circuit. Turn on the power switch. On the left side of the meter are three switches labeled V, A, and Ω . These switches set the function of the meter turning it into a Voltmeter (measure voltage), an Ammeter (measures current), and an Ohmmeter (measures resistance) respectively. This ease of function change has advantages and disadvantages. The disadvantage is that it is very easy to damage the meter with a push of a button by turning it into an Ammeter when it is connected as a Voltmeter.

EXPERIMENT 5

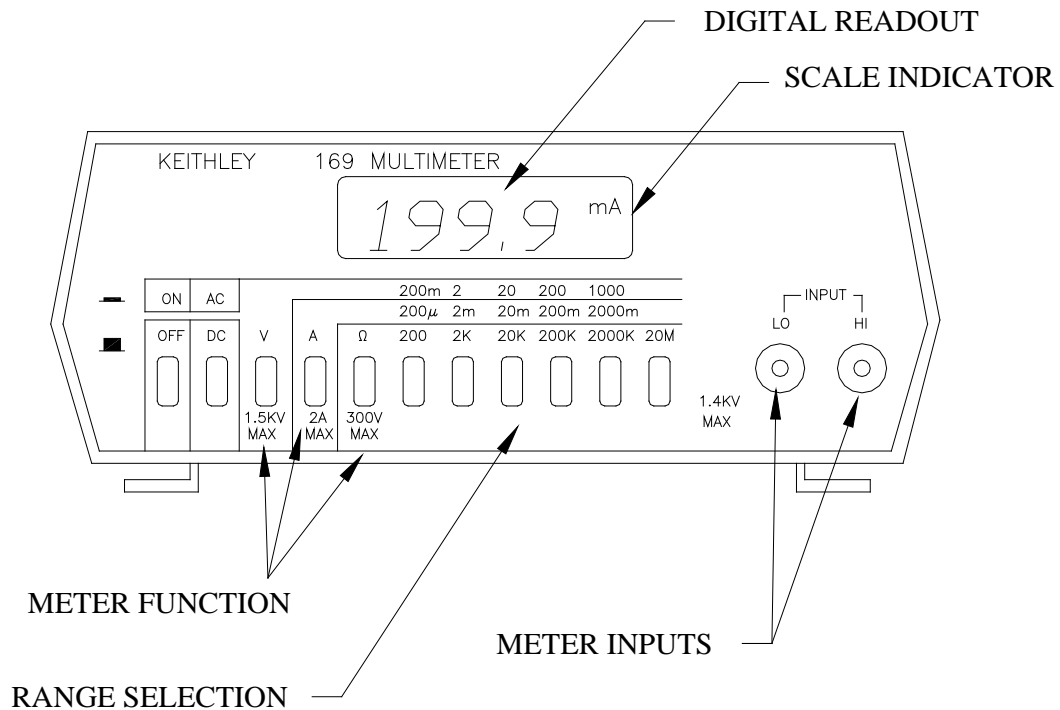


Figure 1 Sketch of the digital multimeter showing important controls.

1) Learning to use the DMM as a Voltmeter. Measure the voltage of a battery in the following manner. Turn on the meter. Set the meter type switch to Volts (V). A small V should appear on the right side of the meter display. See Figure 1 for the location of the SCALE TYPE INDICATOR. Set the DC/AC switch to DC and note that the display indicates a symbol only when the meter is set to AC. Set the scale button to 20V. Plug the test leads into the meter. Take a battery and connect the red lead to the plus (+) terminal on the battery and the black lead to the minus terminal. The display should read »1.50V. These meters are "3-½-digit meters" so sometimes you can get 4 digits displayed on the meter. You can change to the next more sensitive scale. Press the 2V scale button. You should now be able to measure the voltage of the battery to $\pm 0.001\text{V}$ or $\pm 1\text{mV}$. Try going to the next smaller scale and you will see the display with a 1 followed by several blanks. This reading indicates that the meter is *off-scale* and that you need to go to a higher scale in order to make a measurement. Over-scaling the DMM like this will not hurt it, but it would hurt an old style "needle movement" meter. When using the meter, get in the habit of always starting out on the highest scale; then increase the sensitivity by going to a lower scale to get the most digits possible without going over scale.

When the DMM is used as a voltmeter, its internal resistance is very large, »10Meg Ω , so in most applications it draws very little current from the circuit. This allows the reading of the meter for the battery to essentially be equal to the internal voltage of the battery. A voltage measured with little current drawn from it is referred to as the *open circuit voltage*. Now switch back to the 2V scale. Record the VOLTAGE of the battery. The uncertainty in your measurement is ± 1 digit of the smallest decimal of the scale you are on. For example, on the 2V scale the reading is good to $\pm 0.001\text{V}$ or $\pm 1\text{mV}$. On the 20V scale the reading is good to $\pm 0.010\text{V}$ or $\pm 10\text{mV}$.

Reverse the leads of the DMM across the battery, i.e. red to negative and black to positive. Record the voltage reading. How does this differ from your previous reading?

QUESTION 1- If you were measuring a voltage (not the battery) when the scale was set to 200mV what would be the uncertainty in this measurement?

EXPERIMENT 5

OHM's Law - $V = IR$

2) In order to use the DMM as an ammeter it must be wired into the circuit. An ammeter can be thought of as a very sensitive voltmeter with a very low internal resistance. The resistance is so low that the meter acts almost like a piece of highly conductive wire. This allows the ammeter to minimally disrupt the current flowing in the circuit. If we were to accidentally connect the meter across the terminals of a battery, it would be like connecting a piece of wire across the battery. The resistance in the circuit would be very small, so the current would be very large. Alkaline batteries under short circuit are capable of delivering tens of amperes for a short time. The maximum current the ammeter can stand without being damaged is 2 amps. **As a safety precaution, always use a fuse in series with the DMM when using it as an ammeter.** Use the short banana lead and connect the fuse directly into the low, or black side of the DMM. You will learn more about using the DMM to measure current in the next section.

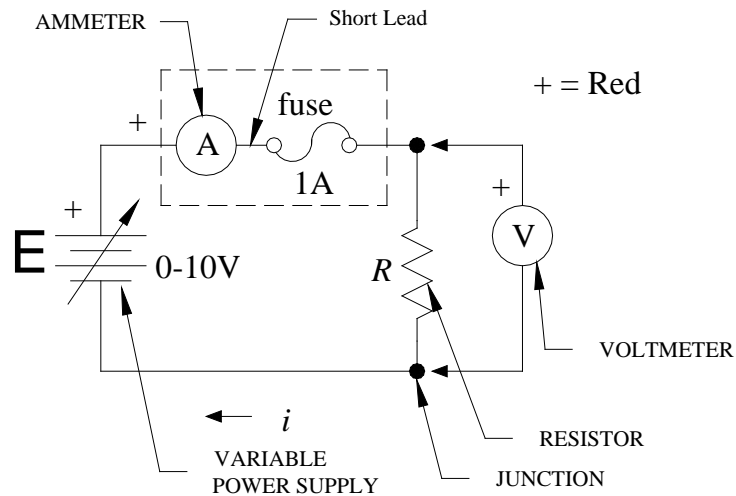


Figure 2 Schematic of the circuit used to measure resistance with symbols defined.

3) Figure 2 is a schematic diagram of the electrical circuit you will be measuring in this part of the lab. Each part of the circuit has a schematic symbol associated with it. Figure 2 has the symbols labeled. Study the figure and try to learn the names of the symbols. To make it easier to wire the circuit, first layout the components, power supply, ammeter, fuse, and resistor on the table just as they are drawn in the schematic. The voltmeter is an external test device so it should be the last element to be connected to the circuit. (This is different than an ammeter which is included in the circuit.) When wiring your circuit, start at the plus (+) side of the power supply and work your way around the circuit, adding wires to the components as indicated in the schematic. Think of the ammeter and fuse as one unit, as implied by the dashed lines in the figures. As you get more familiar with circuits, you won't need to layout the components in the exact geometrical positions shown in the schematic; but when you are first learning, this procedure helps you relate the physical object to its schematic symbol. Wire the circuit as shown in Figure 2, but **do not** connect the last lead to the minus (-) side of the power supply. Have your instructor check your circuit before you proceed.

Turn on the power supply. You will know the circuit is complete if the ammeter is registering current. Make sure the binding posts on the resistor are tightened firmly. Use the DMM to measure the voltage across the resistor. Adjust the voltage until it is **approximately 1V**.

4) Make a data table with columns for Volts and Amps. Vary the voltage from approximately 1V to approximately 9V, taking readings at approximately every volt. (**DO NOT ADJUST THE VOLTAGE TO EXACT INTEGER VALUES.**) Adjust the voltmeter to get as much precision as possible from your measurements. Make a plot of voltage as a function of current on a graph. Label the graph clearly. Find

EXPERIMENT 5

the slope of the line on the above graph using the linest function. The slope of this line should be the resistance R_I . Two times the standard deviation of the slope is the uncertainty in the resistance.

QUESTION 2 - What do you determine R_I to be? Estimate the uncertainty associated with your determination of R_I .

Equivalent Resistance

5) Again wire a circuit as in FIGURE 2, but now use R_2 . (You can just swap the resistor without rewiring the circuit from scratch.)

6) Set the voltage to approximately 5V and measure the current i in the circuit. Now use Ohm's Law to find the resistance. Write an expression for the uncertainty associated with your determination of R and calculate the uncertainty estimate for the resistance. Measure and record the resistance of the last resistor R_3 .

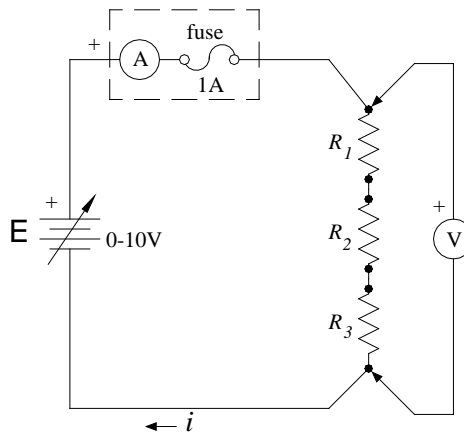


Figure 3 Schematic showing resistors wired in series.

7) Wire the resistors in series as in Figure 3 and again record the voltage and current. (Pick the scales on your meters to get the highest possible precision.) Use your measurements to find the equivalent resistance. Calculate the total theoretical resistance of the resistors in series using the experimental values that you measured previously. Remember that for series resistors:

$$R_{eq} = R_1 + R_2 + R_3 \quad (3)$$

QUESTION 3 - Compare these two results. Do they agree within your uncertainty estimates?

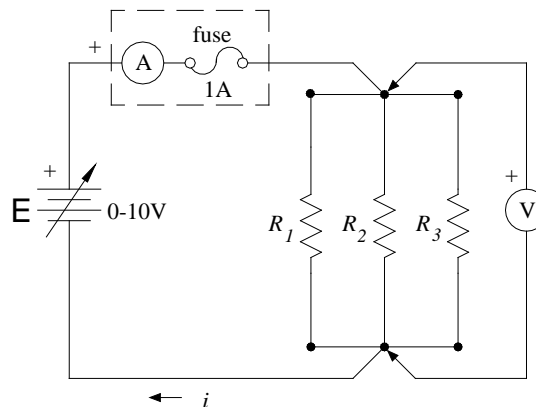


Figure 4 Schematic of resistors wired in parallel.

EXPERIMENT 5

8) Assemble the resistors in parallel as shown in Figure 4. Using your measurements of voltage and current, again calculate the resistance of the network. Again adjust the scales on the meter to get the highest possible precision. For resistors in parallel:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad (4)$$

Calculate the theoretical resistance of the network using the values you obtained in Part 2 above.

QUESTION 4 - Does your measured resistance agree with your theoretical value? Remember the uncertainty in the sum of reciprocals is equal to the sum of the fractional uncertainties. Include an uncertainty estimate for the equivalent resistance.

QUESTION 5 - Summarize the values for ALL of the resistances measured in a table.

Kirchoff's Voltage Law - $\sum V_i = 0$

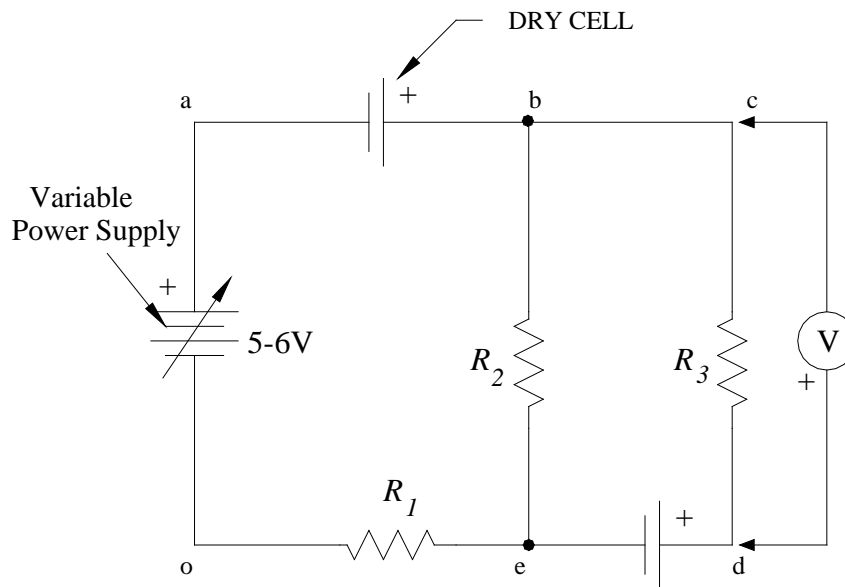


Figure 5 Schematic of the circuit used to study Kirchhoff's loop theorem.

In this part of the experiment you will study the validity of Kirchhoff's loop theorem. This theorem states that the sum of the voltages measured around any closed loop is equal to zero; it is very useful in determining the voltages and currents in many different types of circuits.

9) Build the circuit shown in Figure 5. Set the DMM to DC Voltmeter mode and set the range to 20V. Look at the circuit and notice that there are three separate paths through which current can flow. There is a loop that goes all the way around the outside (rectangle acdo), a loop on the left side (rectangle abeo), and a loop on the right side (rectangle ebcd). Kirchhoff's loop theorem states that the sum of the voltages around any closed loop must equal zero. We will now define a voltage V_{cd} to mean the voltage between point c and point d. You measure this voltage by placing the negative meter lead at c and the positive meter lead at d. See Figure 5 for an example. Look at the right loop and, starting at point e, write the sum of the voltages around the loop:

$$V_{sum} = V_{eb} + V_{bc} + V_{cd} + V_{de}.$$

Now measure the four voltages (change scales if you need to).

QUESTION 6 - Do the sum of these voltages add up to zero. Remember to include an estimate for uncertainty.

EXPERIMENT 5

10) Repeat the above procedure for the left loop. The voltage sum around the left loop is:

$$V_{sum} = V_{oa} + V_{ab} + V_{be} + V_{eo}.$$

QUESTION 7 - Do the sum of these voltages add up to zero. Remember to include an estimate for uncertainty.

11) Now write an expression for the voltage sum around the outside loop and then measure it.

QUESTION 8 - Do your measurements support Kirchhoff's Loop Theorem?

References

Haliday, Resnick, and Walker, *Fundamentals of Physics 7th Ed*, Chapters 26 & 27 (Pages 682-720)

Experiment 6 - Introduction to the Digital Oscilloscope

In this lab you will learn how to take some basic measurements using a digital oscilloscope. These basic measurements include measuring the peak-to-peak voltage, the period, and the frequency of a periodic waveform. You will also measure the frequency range of your voice by singing into a microphone and analyzing the signal on the oscilloscope. When only resistors and AC voltage sources are in a circuit, the peak-to-peak amplitudes of AC voltages sum just like DC voltages. Finally you will investigate the behavior of a diode, which does not obey Ohm's law.

Apparatus:

Tektronix TD2002 digital oscilloscope, Hewlett-Packard function generator, battery, resistors and diode with holders, microphones, banana leads, and BNC-to-banana adapters.

Introduction:

Because of its versatility the *digital oscilloscope* is probably the most widely used instrument in the physics laboratory. It can be used to help to diagnose a defective computer or measure the response of a neuron in a live animal. Its measuring capabilities can be expanded by using *transducers* to turn real world phenomena into electrical signals. A microphone and photodiode are examples of different types of transducers. A microphone can be used to determine the frequency range over which you can sing. The photodiode can be used with a pulsed light source to measure the speed of light.

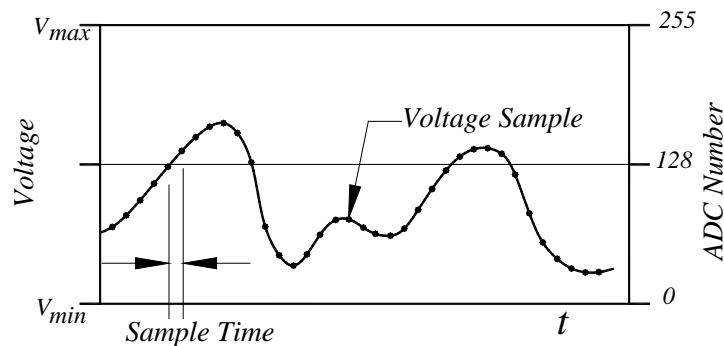


Figure 1 Diagram showing how a time varying voltage is sampled and converted to numbers.

Figure 1 demonstrates how the digital oscilloscope displays voltages similar to the method used to make a digital sound recording. An *Analog-to-Digital Converter* or *ADC* samples the input voltage at fixed time intervals, converts this voltage into a number, and stores these numbers in memory. Once in memory, the signal is displayed on a liquid crystal screen and can be easily measured and analyzed. The TDS 2002 converts the voltages into numbers ranging from $V_{min}=0$ to $V_{max}=255$ and stores 2500 samples. Controls on the oscilloscope allow you to set the values of V_{min} and V_{max} . One big advantage of the digital oscilloscope is that it can capture and display signals that only last for a brief time, such as your signing into a microphone. This makes the analysis much easier than the older style oscilloscopes which some of you may be familiar.

EXPERIMENT 6

AC Waveforms

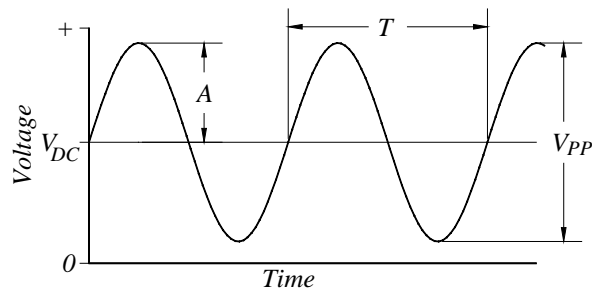


Figure 2 Alternating Current waveform.

As shown in Figure 2 the simplest **AC** or Alternating Current waveform for a time varying voltage $V(t)$ is a sine wave of the form

$$V(t) = A \times \sin(\omega t) + V_{DC} \quad (1)$$

Where A is the amplitude and ω is the angular frequency which is equal to $2\pi f = 2\pi/T$. Where f is the frequency and T is the period. The term V_{DC} represents a constant voltage above or below zero volts, which is defined as **ground**. See Appendix I for more information on Grounding. When measuring the amplitude of a wave on the oscilloscope it is much easier to measure the **peak-to-peak** amplitude V_{PP} which is equal to two times the mathematical amplitude A in Eq 1. From now on amplitude refers to the peak-to-peak amplitude unless otherwise indicated.

Procedure

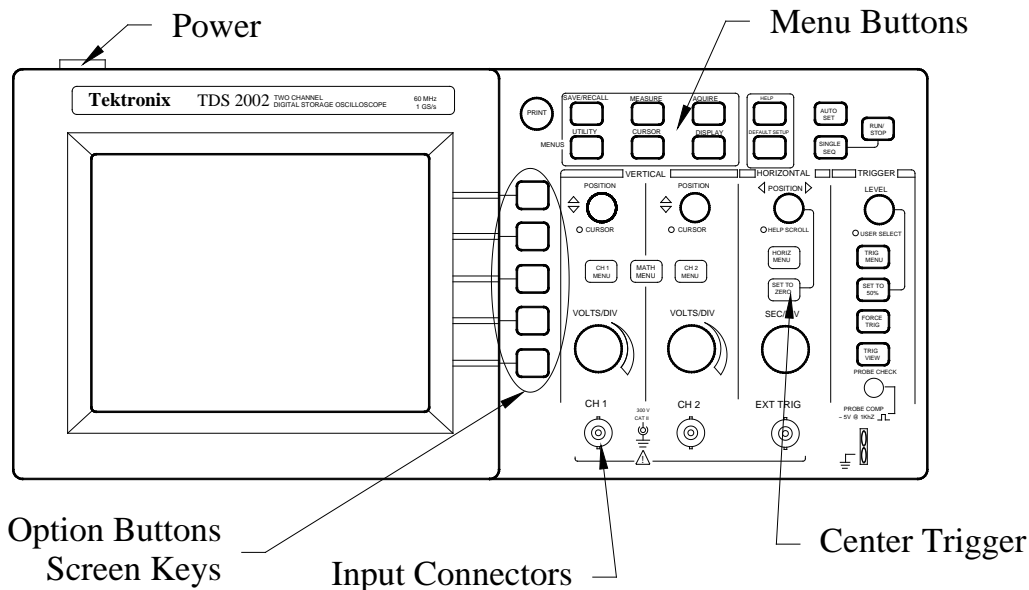


Figure 3 Diagram of the TDS 2002 digital oscilloscope you will use today.

The only way to learn how the oscilloscope works is by experimenting with it. Don't be afraid to push buttons and turn the knobs when trying to find a new signal. You can always undo what you have done by pressing the **DEFAULT/SETUP** button. Learning how to interpret the icons and text on the screen takes some time to learn. The following exercise is designed to get you started on this path.

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1) Push down the power button which is located on the upper left side of the oscilloscope. A screen will appear asking which language you prefer, just wait a minute and this menu will disappear. The oscilloscope remembers the state it was last left in and will start upon in that mode. Press the **DEFAULT/SETUP** button in the upper right of the panel. Then press the yellow **CH1 Menu** button. You should see a screen that looks like Figure 3.

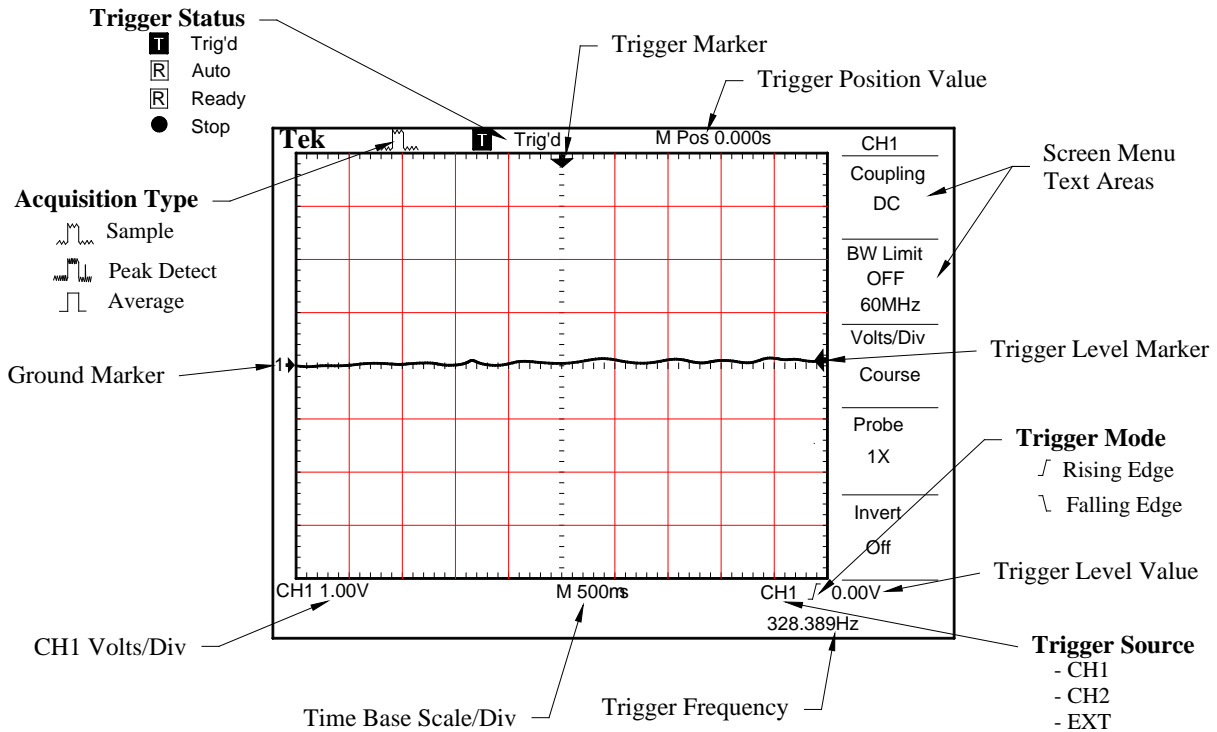


Figure 4 Default display screen with the CH1 Menu turned on.

2) On the right hand side of the display screen are menu areas that are associated with **Option Buttons** or **Screen Keys** on the front panel of the oscilloscope. See Figure 3. Pressing the menu button will change the value associated with that button. Set the **Probe** value to 1X by pressing the menu button next to probe until the screen displays **1X**. Notice the **CH1 Volts/Div** should now be 100mV. Change the value of this to 1.00V by turning the **VOLTS/DIV** knob located under the **CH1** Menu button. See Figure 4. Make sure to set the Probe to 1X every time you turn on the oscilloscope.

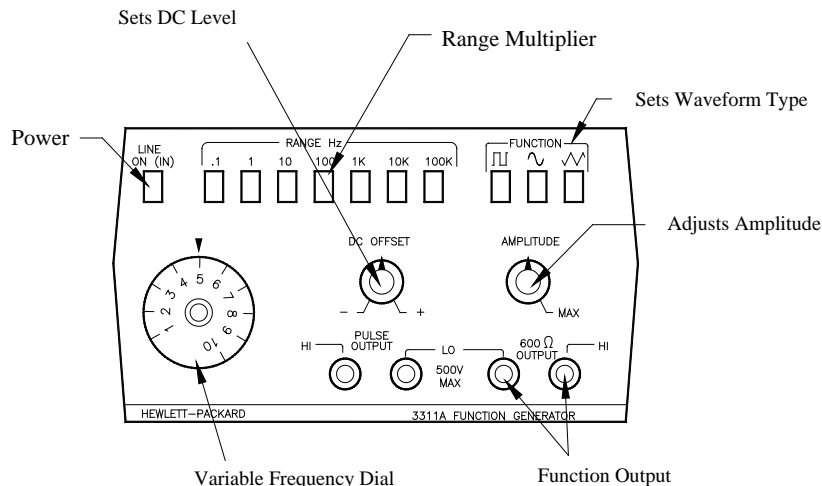


Figure 5 Drawing of the Hewlett-Packard function generator showing the function of controls.

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3) Turn on the HP function generator. Adjust the **Variable Frequency Dial** to 5.0, press the **Range** button to 100 and the **Waveform Selection** to sine wave (~). Turn both **DC Offset** and the **Amplitude** dials so that the markers are straight up as shown in Figure 5. You should now have a sine wave displayed on the screen with about a $2V_{pp}$ amplitude and about 2.5 cycles showing on the screen. The waveform should be approximately vertically centered around the **CH1 Ground Marker** which is on the left side of the screen indicated with an arrow head and the number 1. (See Figure 4). Turn the **DC Offset** knob on the function generator clockwise (CW) so that the wave is moved up about three divisions. Observe the behavior of the wave on the display. The signal is no longer triggered properly. This is indicated in several ways. First the behavior of the wave form is not synchronized on the screen, it appears to drift left or right in an unstable manner as shown in Figure 6. Secondly, the **Trigger Status** (See Figure 4) is **Ready** for a trigger and it is triggering **Automatically**. Finally the Trigger Level Marker (the small left arrow on the right in Figure 4) is out of the amplitude range of the displayed waveform. Correct this condition by adjusting the Trigger **Level** knob located on the upper right side of the panel.

Question 1 - What is the voltage of the DC Offset?

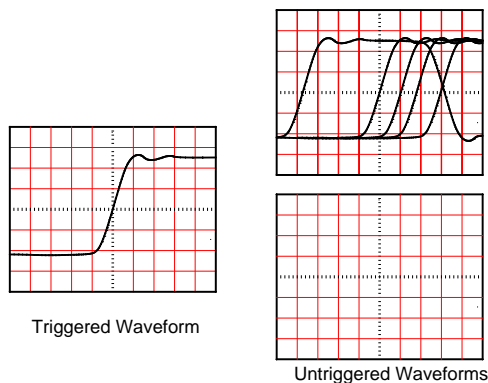


Figure 6 Triggered and untriggered waveforms.

Measuring Amplitude

4) Adjust the DC OFFSET and the AMPLITUDE knobs on the function generator so that the wave is vertically centered about the **CH1 Ground Marker** and the peak of the wave goes up 3.0 divisions and down 3.0 divisions. You will also need to adjust the Trigger Level.

5) The amplitude of this wave should be 6.0V. Here are two ways the oscilloscope can measure it.

a) **Using the Cursors:** Press the **CURSOR** Menu button. Press the Screen Key to change the **Type** to Voltage. You should now see two dashed horizontal lines running across the screen and three more items in the Screen Menu: **Delta**, **Cursor 1**, and **Cursor 2**. Additionally two green LEDs will illuminate next to the **Vertical Position** knobs showing that these knobs are now controlling the on screen cursors. Adjust the dashed lines on the screen so that they run through the top and bottom of the sine wave. Record the amplitude of the wave.

b) **Using the Measure Menu:** Press the **MEASURE** menu button on the panel. You should now see CH1 None in five places in the Screen Menu windows. Press the upper most Screen Key and set the **Source** to **CH1** and the **Type** to **Pk-Pk**. Then press **Back**. The peak to peak amplitude should now be displayed in the upper most menu box.

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QUESTION 2 - How does this measurement compare to the amplitude you measured using the cursors?

Measuring Frequency

6) The frequency of this wave should be 500Hz. Again following are two methods you can use to measure it.

a) **Using the Cursors:** Activate the cursor menu by pressing the **CURSOR** button on the oscilloscope panel. Change the **Type** to **Time**. You should now have two vertical dashed lines on the screen. Use the cursor control knobs to adjust the positions of these lines so they intersect the wave just as it crosses the zero mark and covers one period. The Delta menu item gives you the period and the frequency. Record both of these values for your report.

QUESTION 3 - How does this compare to the expected period and frequency?

b) **Using the MEASURE:** Press the **MEASURE** Key and you should see that you still have the Pk-Pk amplitude measurement in the 1st menu window. Set the **Source** to **CH1** and the **Type** to **Frequency**. Press **Back** and you should have a **Pk-Pk** amplitude and a frequency value in the Screen Menu area. Notice how the oscilloscope remembers your settings when you come back to the same menu. It even remembers these settings after it has been turned off and then back on. Add third a measurement window to display the period. Record the frequency and period for your report.

QUESTION 4 - How do the values for frequency and period compare to the values you obtained using the cursors?

Frequency Calibration Check: You will adjust the numerical dial on the Function generator and use the built in frequency measurements to check the calibration of your function generator.

7) Turn the frequency dial on the Function generator to 1.0. Notice that only about 1/2 of a cycle of the waveform is displayed and the Freq and Period measurements are invalid as indicated by question marks (?). To fix this adjust the **SEC/DIV** knob until you get a valid period. Record these values for your report.

8) Adjust the frequency dial on the Function Generator to 10.0 and adjust the **SEC/DIV** to show just more than 1 cycle and a valid **Freq** and **Period**. Record both.

QUESTION 5 - Are these values what you expect? Does the function generator appear to be linear?

Measuring the Human Voice

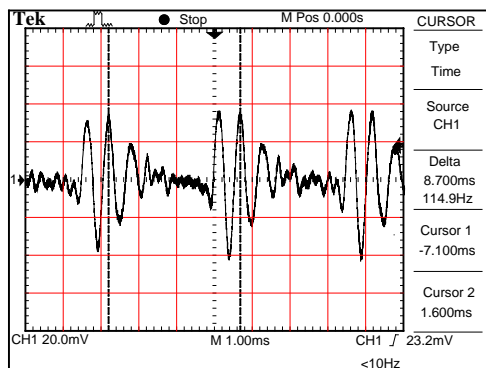


Figure 7 How to measure the fundamental period of a complex human voice waveform.

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9) Disconnect the function generator from the function generator and connect the microphone to **CH 1**. You will probably need to set the **VOLTS/DIV** to its most sensitive scale (5mV/div) by turning the knob CW. Sing a steady tone into the microphone as high as you can and adjust the horizontal time base and the **VOLTS/DIV** until you get a good steady trace and a valid frequency reading while singing. To capture your voice for analysis press the **RUN/STOP** button in the upper right corner of the oscilloscope panel. If you stop singing before the capture or don't sing loud enough, you won't have a trace. Use the cursors to measure the period. Now try to measure the frequency range over which you can sing. Sing the highest note possible and capture it. Use the **CURSOR** and **MEASURE** menus to find the period and frequency and record the values. Make a sketch of the waveform in one of the grids provided at the end of the lab write-up. Include the **VOLTS/DIV** and **SEC./DIV** in your sketch. Also mark the period of your voice on your sketch.

QUESTION 6 - Do the two methods for determining the frequency and period agree? If not, explain what might be happening.

10) Now sing at as low a pitch as possible. Capture and sketch the waveform in one of the scales provided at the end of the lab. Include the oscilloscope settings and mark the period of you voice on your sketch. If the waveform is not sinusoidal, the "fundamental" frequency is based on the time it takes the waveform to repeat itself. See the example in Figure 7. Make sure you show this on your sketch. Use the cursor and measure menus to find the lowest fundamental frequency at which you can sing. Record the values from both methods.

QUESTION 7 - Do the two methods for determining the frequency and period agree? If not, explain what might be happening.

11) Disconnect the microphone from the oscilloscope.

Resistors and AC Voltages

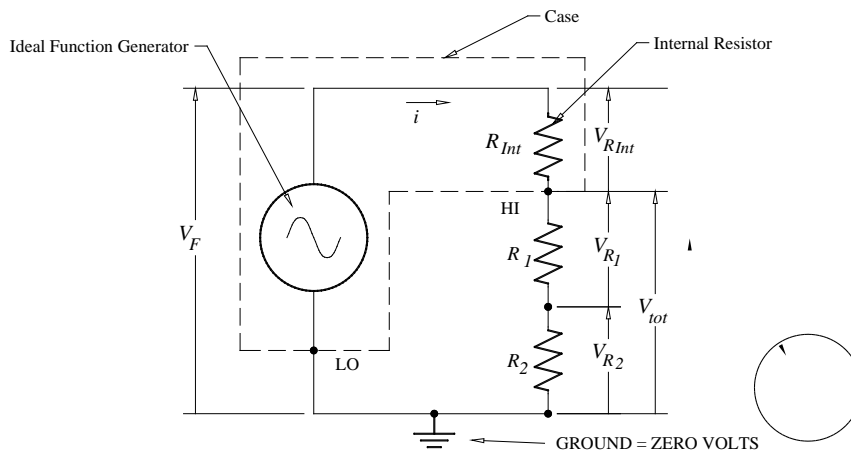


Figure 8 Function generator connected to two resistors in series.

When only resistors are involved in AC circuits the peak-peak voltages can be treated just like DC voltages and used to determine the peak to peak current in a circuit. Kirchoff's loop theorem and Ohm's Law can be used to evaluate the circuit just as if it were DC only. Figure 8 represents the function generator connected to two resistors in series with the voltages drawn as vectors point up from ground. The convention is that voltage **sources** are drawn on the left and voltage **loads** are drawn on the right. The function generator is represented by an ideal AC voltage source V_F in series with an internal resistor R_{Int} . A dashed line indicates the case of the function generator. The output posts of the generator are indicated by two dots labeled HI and

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LO. Since all voltages are referenced to ground the voltage source, V_F , is represented as a vector pointing from ground up. Imagine this as being equivalent to a positive DC battery. As current flows from this source through the three resistors R_{int} , R_1 , and R_2 voltage is dropped as indicated by the three vectors representing the voltage across each of these resistors. Treating these voltages like vectors you should visually see that

$$V_F = V_{R_{int}} + V_{R_1} + V_{R_2} .$$

Using $V=iR$ to substitute for the voltages

$$V_F = iR_{int} + iR_1 + iR_2 . \quad (2)$$

Also from Figure 8 you should see that

$$V_{Tot} = iR_1 + iR_2 \quad (3)$$

and solving this for i yields

$$i = \frac{V_{Tot}}{R_1 + R_2} . \quad (4)$$

Finally solving Equation 2 for R_{int}

$$R_{int} = \frac{V_F - V_{Tot}}{i} . \quad (5)$$

One thing that should be immediately obvious from this equation is that as soon as current starts to flow from the function generator the voltage across the two resistors V_{tot} is less than the ideal voltage V_F . This phenomena will show up in future experiments.

12) In this step you are going to learn how to make an 8.0V_{pp} waveform with 0.0V DC-offset. This will be the standard waveform you will use when working with the oscilloscope in future labs. Connect the oscilloscope to the HI and LO function output of the function generator. (the terminals on the right side) The ground (black) side of the oscilloscope should be connected to the LO side of the function generator. Set the frequency of the function generator to 10KHz and the amplitude knob to about mid-range. Set the Volts/Div for CH1 on the oscilloscope to 1V/Div. You should see a sine wave on the oscilloscope. If you don't, try adjusting the amplitude knob until you do. Adjust the DC OFFSET knob on the function generator until the trace on the oscilloscope is symmetrical above and below the CH1 ground marker. The DC OFFSET is now set to 0.0V. Now when you adjust the amplitude on the function generator, the sine wave will stay symmetric about the horizontal center of the oscilloscope. Adjust the amplitude knob so that the peak-to-peak voltage is 8.0V. When set correctly the top and bottom of the wave should touch the top and bottom edges of the screen. If you have the CH1 Measure menu turned on and displaying peak-to-peak voltage, you will notice that it is very difficult to get the amplitude to be exactly 8.00V as the amplitude knob on the function generator is a bit coarse. Remember that ground as a potential equal to zero volts and to which all measurements are referenced, so the voltage from the function generator goes to +4.0V and down to -4.0V with respect to ground. Since the input impedance of the oscilloscope is about 20Meg Ω the voltage measured is V_f .

13) Disconnect the oscilloscope from the function generator and connect the resistors labeled R_1 and R_2 between the HI and LO Function outputs as shown in Figure 8. Then connect the oscilloscope to measure and record the voltage across both resistors, V_{Tot} , using both the CURSOR and MEASURE Menus. Disconnect the resistors from the circuit and use a digital multimeter (DMM) configured as an ohmmeter to measure the resistances of R_1 and R_2 .

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Remember to pick the scale on the meter to get as much precision as possible in your measurement.

QUESTION 8 - Use your measured values for the resistors and Eqs 4 and 5 to determine the internal resistance of the function generator R_{Int} and compare this value to that written on the function generator. (Don't worry about uncertainties for this comparison.)

The Ratio of Voltages

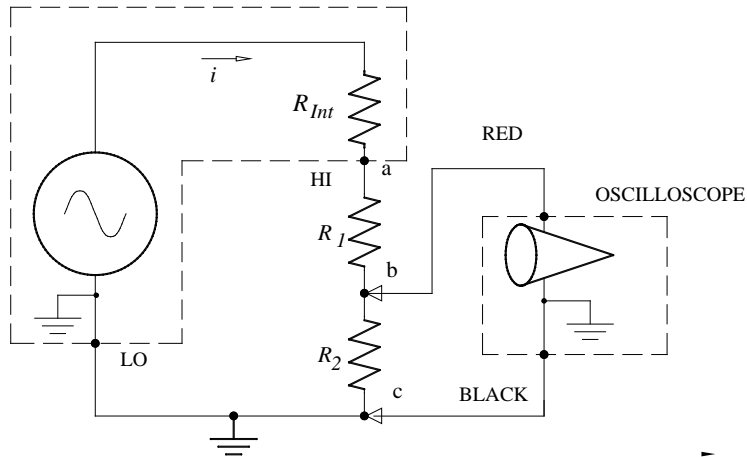


Figure 9 Diagram showing how to measure voltage across R_2 .

Looking at the ratio of the voltages on the two resistors in Figure 8 you can see that:

$$\frac{V_{R_1}}{V_{R_2}} = \frac{i R_1}{i R_2} = \frac{R_1}{R_2}$$

You already have values for R_1 and R_2 . You will now use the oscilloscope to obtain values for V_{R_1} and V_{R_2} to test the above equation.

14) Change the leads on the oscilloscope to measure the voltage across R_2 as shown in Figure 9. Use the CURSOR and MEASURE Menus to measure and record V_{R_2} .

15) In order to measure V_{R_1} it is necessary to exchange the places of R_1 and R_2 in the circuit as shown in Figure 10. To see why it is necessary to swap the places of the resistors, look at Figure 9. If the black lead of the oscilloscope were placed at (b) and the red lead at (a), then point (c) and point (b) would both be at ground (zero volts). Resistor R_2 would be "shorted" by the internal connections to ground in the oscilloscope and the function generator; this would effectively remove R_2 from the circuit, leaving only R_1 .

EXPERIMENT 6

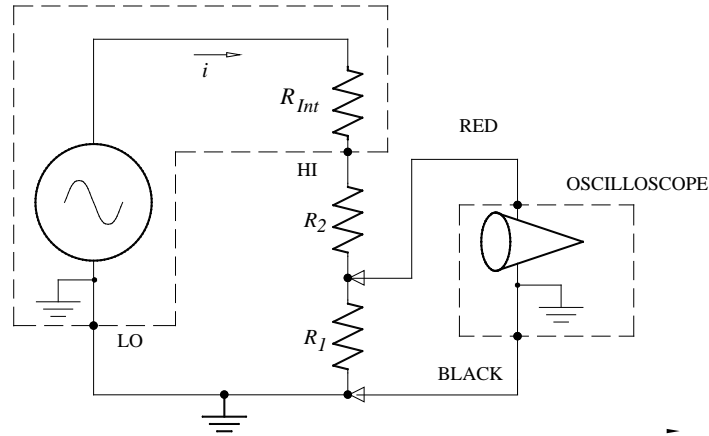


Figure 10 Diagram showing how resistor positions are exchanged to measure V_{R1} and V_{R2} .
 QUESTION 9 - Compare V_{R1}/V_{R2} to R_1/R_2 . Don't forget uncertainty estimates.

The Diode, a Non-Ohmic Device

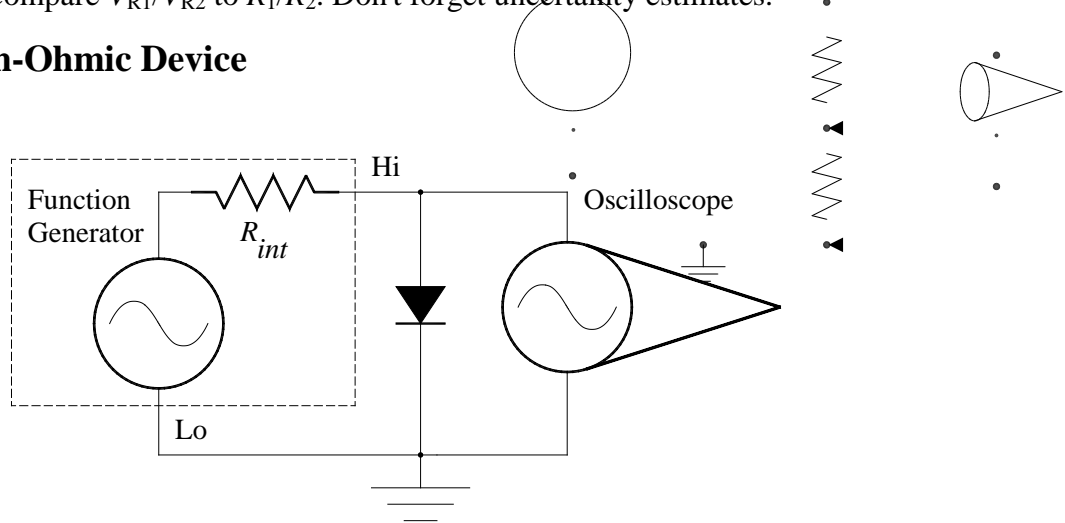


Figure 11 Diagram of a Diode connected to the function generator and oscilloscope.

16) Set the output of the function generator to be an 8.0V peak-to-peak 10.0kHz sine wave with no DC offset. Set the voltage scale of the oscilloscope so that the middle of the vertical scale is ground and the signal described above extends from the top of the screen to the bottom. Adjust the time scale to show 2 to 3 cycles of the wave form.

17) Connect the diode to the function generator and oscilloscope as shown in Figure 11. Sketch the waveform and again record the VOLTS/DIV and SEC./DIV.

QUESTION 10 - Think of the diode as a variable resistor. As the diode is drawn in Figure 11:

- a) Is the resistance of the diode large or small when the voltage is positive? Explain your reasoning.
- b) Is the resistance of the diode large or small when the voltage is negative? Explain your reasoning.

You will see this device again in lab when you build a radio. As you complete the next couple of labs see if you can think of some applications of a device that behaves like this.

EXPERIMENT 6

Appendix I: Grounding

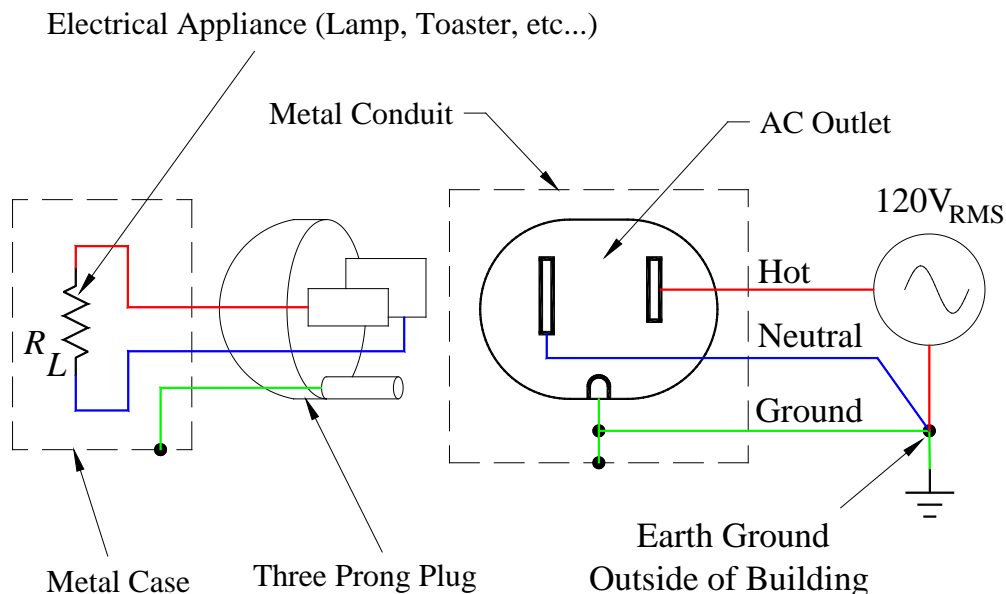


Figure 12 Diagram showing how standard ac power is wired inside a building.

Figure 12 shows a simplified schematic of how 120VAC power is wired inside a typical building. The main purpose of this system is to provide safety for the occupants. Look at the diagram of an AC outlet. The half-round socket on the bottom is the **Ground** connection. Ground is literally the ground we stand on and the AC power we use in our homes is referenced to this potential source. For safety, all conducting metal objects with AC wiring have an electrical connection made to Ground. This includes the **metal conduit** that wires run in and any metal furniture or structures that have wiring around them. Look at the outlet in Figure 12 again, the short socket on the right is called the **Hot** side. You can think of this just like a sine wave from the function generator with peak-to-peak amplitude of $2 \times \sqrt{2} \times 120V_{RMS} = 338V$ and a period of $1/60s$. The socket on the left side of the outlet is known as the **Neutral** or **Return**. In order to complete a circuit so that current flows, a **load resistance**, R_L , must be connected between the Hot and the Neutral. This is just like the HI and LO sides on the HP function generator. The load resistance is simply any type of electrical appliance such as a lamp, hair dryer, etc...

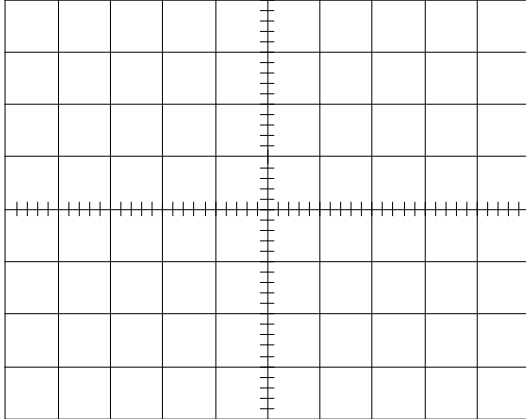
Just outside of the building the AC Neutral wire is electrically connected to the Ground wire. This has the effect of forcing the potential of all metal objects inside the building to Ground potential. If a Hot wire inside an electrical conduit or an appliance were to break and touch the metal case, current would flow from the Hot to the Neutral through the Ground path, but the metal case would never get above Ground potential. See Figure 12. This would prevent an electrical shock. This extra hidden connection is the reason you needed to swap the places of resistors R_1 and R_2 when you were trying to measure the sum of the voltages around a current loop.

Imagine what would happen to you if you were to stick your finger in the Hot side of an AC outlet - current would flow from the Hot wire through your body to Ground, then to the Neutral point outside of the building. At best you'd receive a nasty shock and at worst you could be electrocuted. To prevent this last scenario from happening, a device known as a **Ground Fault Interrupt** (GFI) is employed where electrical shocks might be a possibility. A GFI circuit watches for current flow from the Hot to Ground and very rapidly, in microseconds, disconnects the Hot side of the circuit.

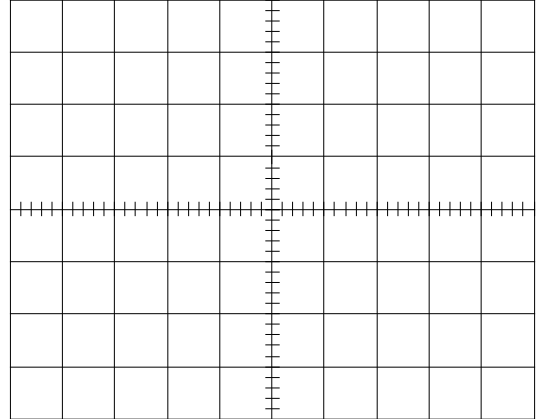
EXPERIMENT 6

Oscilloscope Scales For Waveform Sketches

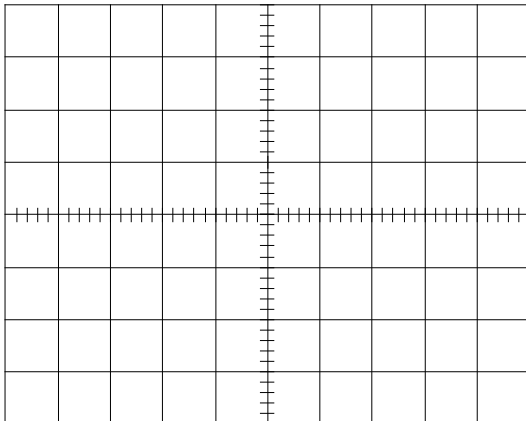
Sketch of _____
Volts/Div _____ Sec./Div. _____



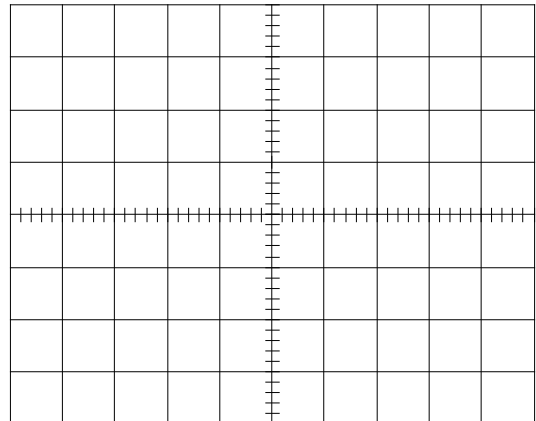
Sketch of _____
Volts/Div _____ Sec./Div. _____



Sketch of _____
Volts/Div _____ Sec./Div. _____



Sketch of _____
Volts/Div _____ Sec./Div. _____



EXPERIMENT 6

Experiment 7 - RC Circuits

You will be introduced to the exponential charge and discharge cycles of a capacitor in series with a resistor (i.e., a “series RC circuit”). The maximum speed of digital circuits, such as those found in computers, are primarily a function of the RC time constant of the circuits. The behavior of capacitors in series and parallel will be investigated. Finally a diode will be used with a capacitor to build a DC power supply.

Apparatus:

TDS oscilloscope, HP function generator, 10k Ω & 100k Ω resistors, capacitors, diode, component holders, and banana leads.

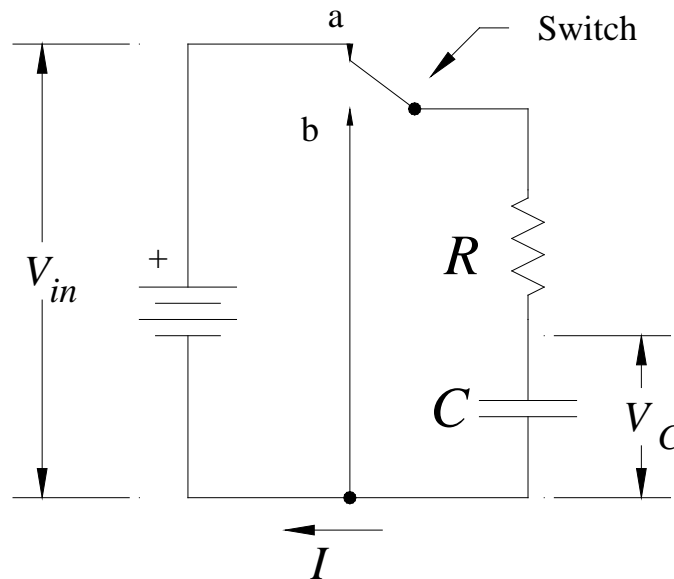


Figure 1 Diagram of a circuit used to charge and discharge a capacitor.

Introduction

A **capacitor** is a device that can store electrical energy. It basically consists of two conductors separated by an insulator. When a capacitor is connected in a DC circuit, equal and opposite charges build up on the two conducting plates, leading to a potential difference (V) between the plates. For a capacitor the potential V is proportional to the charge q and inversely proportional to the capacitance C . Algebraically, this can be written as $V = q/C$. Figure 1 is a diagram of a circuit that can be used to charge and discharge a capacitor through a resistor. When the switch is in position **a**, the capacitor is connected in series with the resistor R and the battery. Current will flow into the capacitor until its voltage equals that of the battery or the switch is thrown. The voltage on the capacitor after the switch is moved to position **a** is given by:

$$\text{(Charge)} \quad V_c = V_o (1 - e^{-t/(RC)}) \quad (1)$$

Initially, at the time the switch is closed ($t = 0$), the voltage on the capacitor is zero. As time increases the flowing current charges the capacitor up to the voltage of the battery, V_o . When the switch is in position **b**, current flows from the capacitor through the resistor, and the capacitor discharges. Current will continue to flow until the voltage on the capacitor equals zero or the switch is thrown. After the switch is moved to **b**, the voltage on the capacitor is given by

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$$\text{(Discharge)} \quad V_c = V_o e^{-t/(RC)}. \quad (2)$$

The above equation represents **exponential decay**. Exponential functions are useful for describing the behavior of a wide range of phenomena such as radioactive decay and the growth of bacteria. If a graph is made of the natural logarithm of V_c as a function of time, the graph will be a straight line. The negative reciprocal of the slope of this line is equal to the **time constant**, RC . This is easy to show if you first take the logarithm of both sides of Equation 2

$$\begin{aligned} \ln(V_c) &= \ln(V_o e^{-t/(RC)}) \\ \ln(V_c) &= -\frac{t}{RC} + \ln(V_o) \\ y &= m x + b \end{aligned} \quad (3)$$

From this you can see that the intercept b equals $\ln(V_o)$ and the slope m is the negative reciprocal of the time constant RC . This is one way that you can graphically measure the time constant.

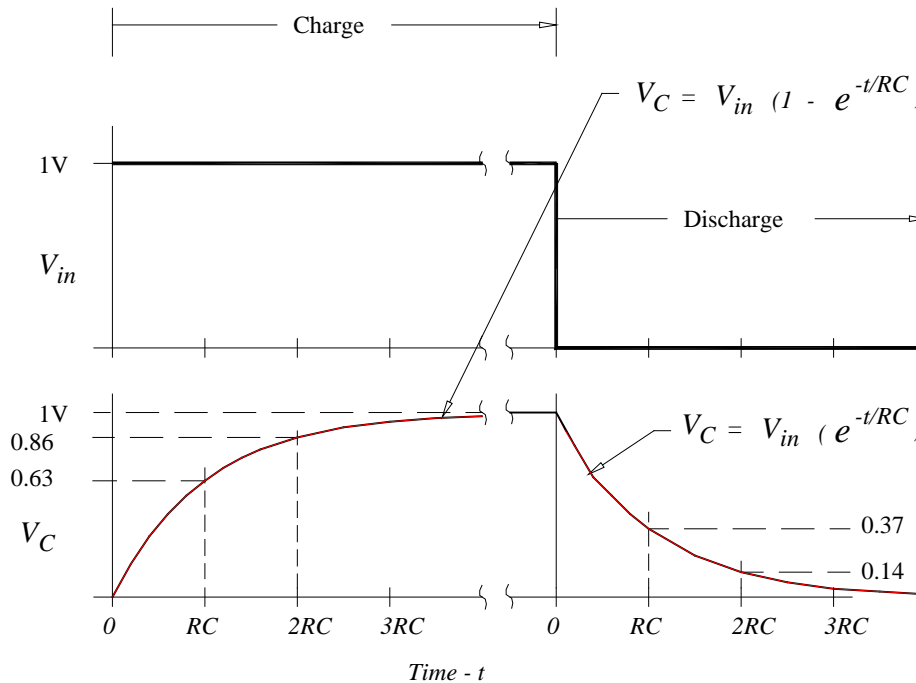


Figure 2 Graphs of the voltage from the switch and the voltage on a capacitor as a function of time as it is charged and discharged.

Look at Equation 2 and notice that if the time t is equal to RC , then Equation 2 becomes $V_c = V_o e^{-1}$. The number e is the base of the natural logarithms and is equal to approximately 2.718. So e^{-1} is just equal to $1/2.718 = 0.368$. V_c is therefore equal to $0.368V_o$ at this time. Figure 2 shows a generalized diagram of the charge and discharge cycle of an RC circuit. The graph on the top shows the voltage applied to the resistor and capacitor, and the graph on the bottom shows the voltage on the capacitor with respect to time. By measuring the time it takes the voltage to fall from V_o to $0.368V_o$, the time constant RC can be determined. Knowing R , we can determine the magnitude of C . This is the “ $1/e$ method” of measuring the time constant. It is also possible to measure the time constant by looking at the charging cycle. Today's lab involves measuring time constants to determine the capacitance C .

The capacitance of a capacitor is measured in Farads, abbreviated F. A one Farad capacitor in series with a one Ohm resistor would have a time constant of one second. A one

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Farad capacitor is a VERY LARGE capacitor. Typically capacitors are measured in microfarads (µF) (1 nF = 10⁻⁶F). **You should report your capacitances in microfarads.**

Capacitors are individual components and can be built into various circuit configurations. Just like a network of resistors, a network of capacitors will act like one single capacitor, and the network has an equivalent capacitance, C_{eq} . For capacitors in parallel, the equivalent capacitance is:

$$\text{(Parallel)} \quad C_{eq} = \sum_{i=1}^n C_i = C_1 + C_2 + C_3 + \dots + C_n \quad (4)$$

For capacitors in series the equivalent capacitance is:

$$\text{(Series)} \quad \frac{1}{C_{eq}} = \sum_{i=1}^n \frac{1}{C_i} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots + \frac{1}{C_n} \quad (5)$$

Measuring RC Time Constants By The “1/e Method”

In this part of the experiment you will learn how to determine the RC time constant of a discharging capacitor by measuring the time it takes the voltage to decay to “1/e” of its original value.

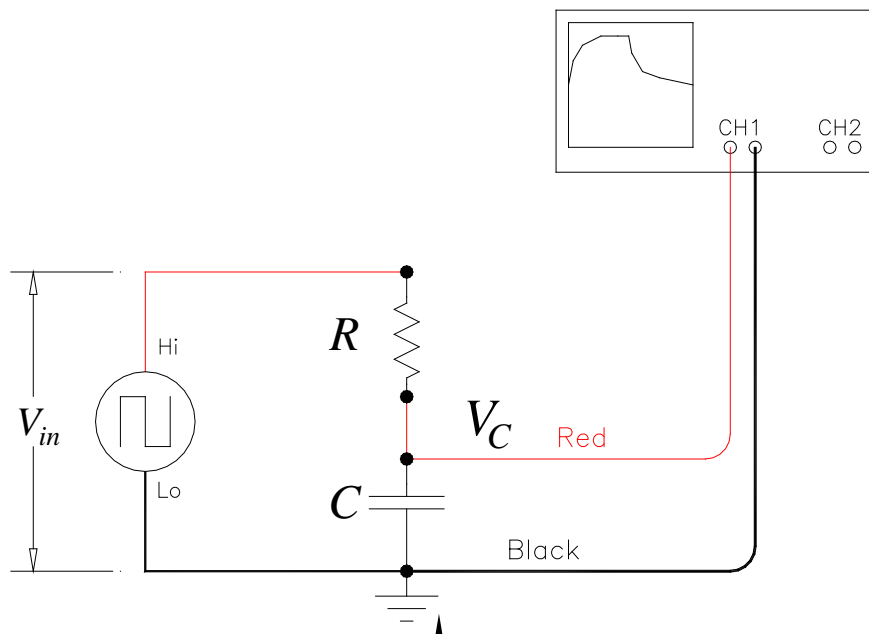


Figure 3 Diagram showing how to connect a resistor and capacitor in series to a function generator.

1) First turn on the function generator and oscilloscope and connect the 600W Output to CH1 of the oscilloscope. Set the frequency of the function generator to 500Hz. Push the yellow CH1 button on the oscilloscope and make sure Probe is set to 1X. Press the Trigger menu and set the trigger source to CH1 and the Slope to Falling. Adjust the amplitude of the function generator so that you have a 8.0V_{pp} (i.e., 8.0 volts peak-to-peak) square wave coming from the function generator with 0.0V DC-offset. (See step 12 in "Introduction to the Digital Oscilloscope" if you can't remember how to do this.) You may have to adjust the Sec./Div on the oscilloscope. Disconnect the oscilloscope from the function generator and build the circuit shown in Figure 3 using the 10kΩ resistor and the capacitor labeled C₁. Then connect the oscilloscope to the circuit

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as shown in Figure 3. Make sure the binding posts on the component blocks are firmly screwed down.

2) **Adjust the controls on the oscilloscope and the frequency of the function generator** until you have a waveform that looks like to the one in Figure 4. Refer to your notes and the write-up for the experiment on learning the oscilloscope if you need help. When you have everything properly adjusted, the waveform should start from the upper left corner of the screen and go all the way to the bottom. Have your lab instructor check your setup at this point.

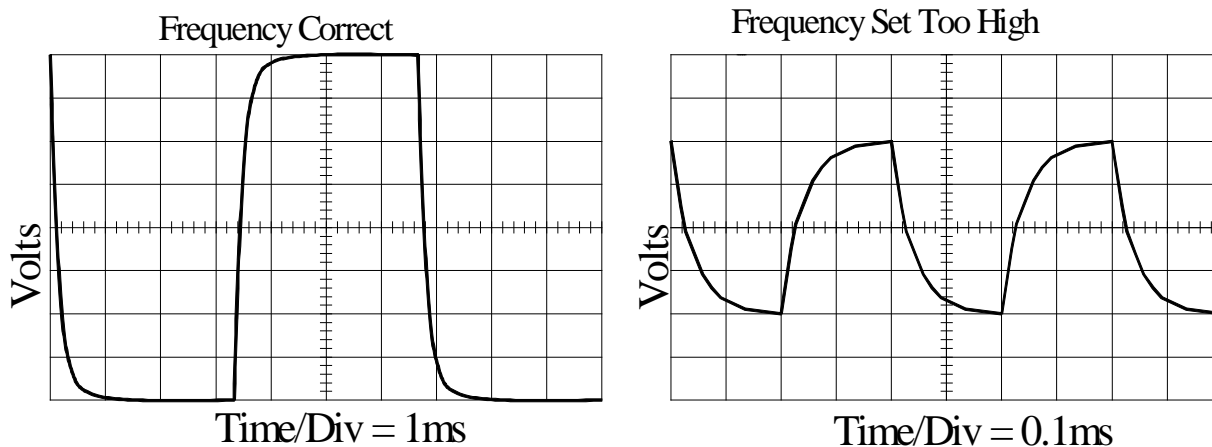


Figure 4 Sketch of RC waveforms. The left shows the frequency adjusted to allow the capacitor to fully charge and discharge. The right shows what happens when the frequency is set about 10 times too high so the capacitor doesn't have enough time to fully charge and discharge. Note that the Sec./Div. on the right is less than on the left.

3) Carefully adjust the horizontal position so that the signal starts in the upper left corner of the screen. This is the time the capacitor just begins to discharge (the time the switch just closed in the simple model). If the trace does not go all the way to the top and bottom the frequency of the function generator may need to be adjusted.

4) You are going to measure the time it takes the capacitor to discharge to $1/e$ of its initial value. For the discharge cycle, see Figure 2; the voltage after one time constant is $0.368V_0$. The function generator has been set so that V_0 is 8.0V (+4.0 to -4.0V) so $0.368 \times 8.0V = 2.94V \approx 2.9V$. One RC time constant is equal to the time it takes the voltage on the capacitor to go from 8.0V to 2.9V. Turn on the Cursors and move one of the cursor to the bottom of the screen so that it is at -4.0V. Move the other cursor so that the difference between the two is 2.94V. Measure the time it takes the voltage to go from the top left most corner to when it crosses this line. Remember to adjust the Time Base knob and horizontal position on the oscilloscope to get at least 3.3 horizontal divisions before the trace crosses the 2.9V level, thus maintaining 3% accuracy in your measurement. This time is RC .

5) Find the value of the capacitor by dividing the time constant RC by the value of the resistor.

QUESTION: What is the uncertainty in the capacitance? (Hint: What is the percentage accuracy of the oscilloscope?) Call this value C_1 .

6) Measure the value of the other capacitor you have by the above method. Note that you may have to change the frequency of the function generator so that you see the capacitor get fully charged. See Figure 4. Call the value for this capacitor C_2 and again determine the uncertainty in your measurement.

EXPERIMENT 7

Parallel and Series Capacitors

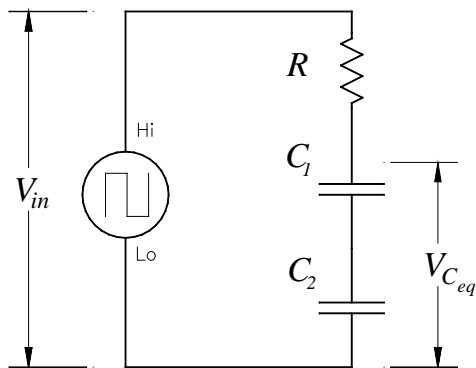


Figure 6 Diagram showing capacitors wired in series.

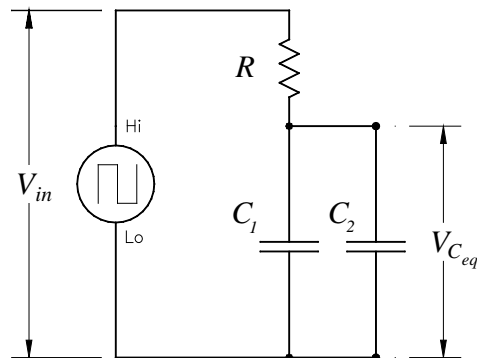


Figure 7 Diagram showing capacitors wired in parallel.

- 7) Now connect the two capacitors in series as shown in Figure 6.
 - 8) Measure the effective capacitance by the I/e method as outlined in step 3 and 4.
 - 9) Using the values of C_1 and C_2 that you previously measured, calculate the theoretical equivalent capacitance of this network.
 - 10) Question: Does $C_{exp} = C_{theo}$ within your ability to determine it?
 - 11) Now connect your two capacitors in parallel as shown in Figure 7.
 - 12) Measure the effective capacitance by the I/e method. Make sure to check the frequency.
 - 13) Using the values of C_1 and C_2 that you previously measured, calculate the theoretical equivalent capacitance of this network.
- Question: Do your measured values agree with your predicted values?

A Diode in Action - the Half-wave Rectifier

In last week's lab you observed that a diode does not obey Ohm's Law. Now you will be able to see why it can be desirable to have a device with such behavior. Construct the circuit in Figure 8 using the diode and a 100k Ω resistor, but for the time being omit the Capacitor. When using diodes it is important to pay attention to which way you install them in a circuit. The tip of the arrow in the schematic diagram points in the direction the diode allows current to flow. In the physical diode, the end with a stripe corresponds to the tip of the arrow in the schematic.

- 14) Push the blue CH2 button to turn on the **oscilloscope's** CH2, set the Volts/Div to 1.0 and set the midpoint of the voltage scale to be Ground and the Probe multiplier to 1X. To do this temporarily set the coupling switch to GND, then adjust the vertical position knob of the CH2 trace to the middle of the screen and then flip the coupling switch back to DC. Set the frequency knob on the **function generator** to output a 1.0kHz sine wave with amplitude 8.0Vpp and no DC offset. (To remove any dc offset, adjust the DC-offset knob on the **function generator** until the trace is vertically centered on the screen of the oscilloscope. To set the amplitude to 8.0V, adjust the Amplitude knob on the function generator until the trace goes from the top to bottom of the scale on the oscilloscope.) Set the Sec./Divisions on the **oscilloscope** so you can see a couple cycles of the sine wave. View both CH1 and CH2 simultaneously on the oscilloscope by pressing the CH1 and CH2 until you can see both tracers. Set the Volts/Div. on CH1 to 1.0Volts/Div., the

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Probe multiplier to 1X, and the midpoint of the voltage scale to be ground. Press the Trig Menu button and set the trigger source to CH2. Sketch the output of the function generator in one color along with the voltage drop across the resistor in another color in the grid patterns provided at the end of this write up.

This circuit is referred to as a **half-wave rectifier**. It accomplishes the important task of **rectification** where an **alternating current** (*ac*) in which the direction of the current flow is alternating back and forth, is converted to a **direct current** (*dc*) in which the direction of the current flow is not changing over time. Rectification is the first step in building a constant voltage potential source. It is also a critical step in the radio circuit that you will assemble later this semester. It is called a **half-wave rectifier** because only half of the waveform is turned into current in the resistor.

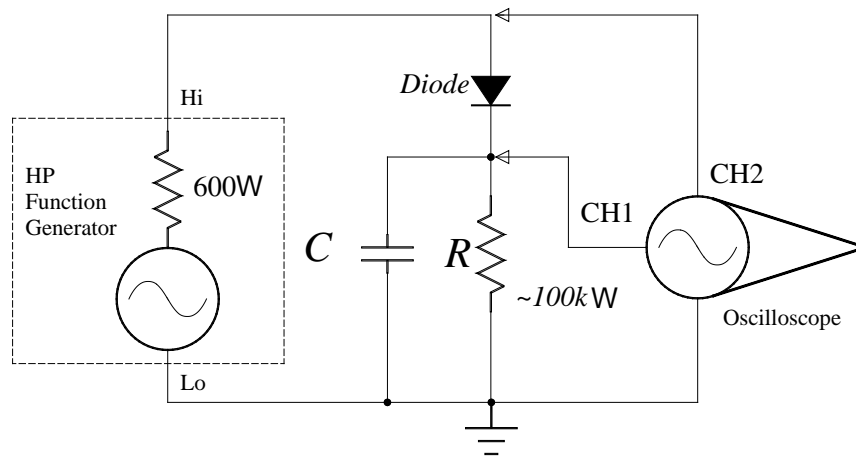


Figure 8 Schematic diagram of a simple DC power supply.

15) Now add capacitor C_1 into the circuit as shown in Figure 8. Sketch the wave forms for CH1 and CH2 as you did above. Your sketches for the voltage across the resistor should look similar to that shown in Figure 9.

16) Repeat the above for capacitors C_2 and C_3 .

17) Question: What is the period in milliseconds of a 1kHz sine wave?

18) Calculate the RC time constants for each of your sketches using 100kΩ for R and your values for C . Write the RC values in the appropriate blanks on the sketches.

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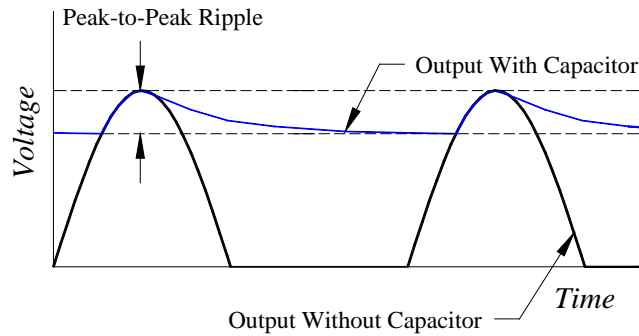


Figure 9 Wave forms for the voltage across the $100k\Omega$ resistor. Note the function generator voltage is not shown.

19) Question: Looking at your sketches, what happens to the amplitude of the peak-to-peak ripple as the value of the capacitor increases? Explain why this happens in terms of the RC time constant.

20) Question: Explain why the "ripple" voltage is asymmetric. Think about how the current flows in the circuit when the capacitor is charging and then when it is discharging. Which value of capacitor would make the best constant voltage potential source?

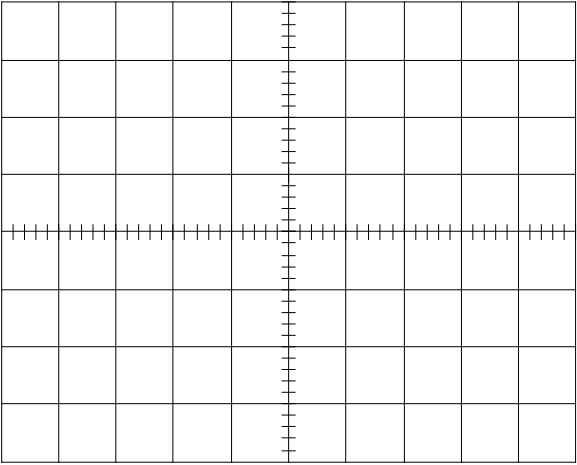
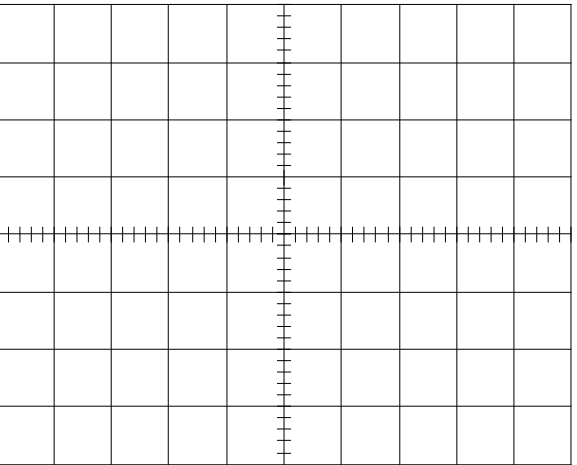
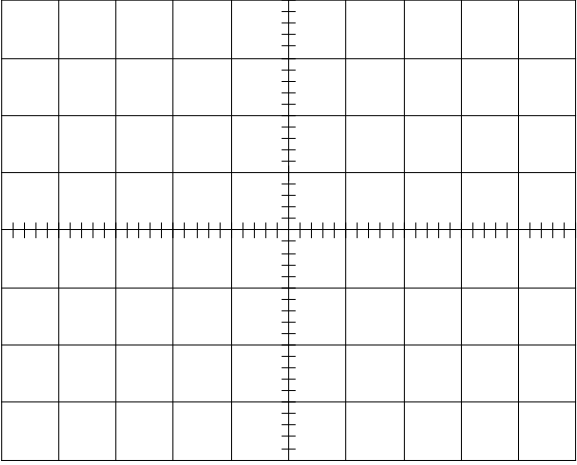
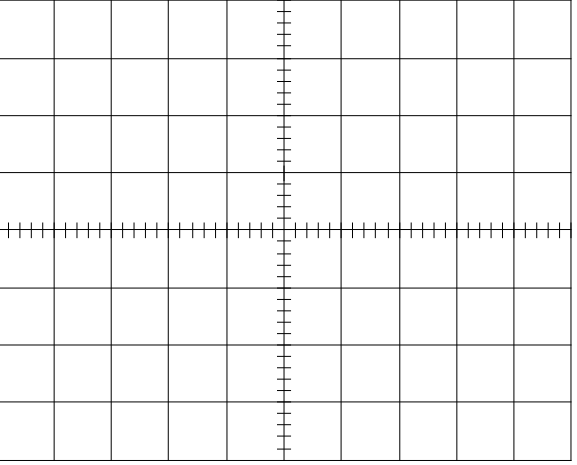
References

Haliday, Resnick, and Walker, *Fundamentals of Physics 7th Ed*, Chapter 27-9 (Pages 720-722)

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Oscilloscope Scales For Waveform Sketches

<p>Sketch of output when using no capacitor:</p> <p>Volts/Div _____ Sec./Div _____</p> 	<p>Sketch of output when using $C_1 = \text{_____} \mu\text{f}$ $RC = \text{_____} \text{ms}$</p> <p>Volts/Div _____ Sec./Div _____</p> 
<p>Sketch of output when using $C_2 = \text{_____} \mu\text{f}$ $RC = \text{_____} \text{ms}$.</p> <p>Volts/Div _____ Sec./Div _____</p> 	<p>Sketch of output with $C_3 = \text{_____} \mu\text{f}$ $RC = \text{_____} \text{ms}$.</p> <p>Volts/Div _____ Sec./Div _____</p> 

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Experiment 8 - AC Circuits

In this lab you will learn about the frequency-dependent behavior of electrical circuits containing *reactive* components such as capacitors. You will observe that the amplitudes of the voltages in a circuit with reactive components do not obey Kirchoff's Loop Theorem. The current flowing in a circuit is determined by a property called *impedance*. The impedance of a resistor is constant over all frequencies. The impedance of a reactive component varies with frequency. Since impedance determines the current in a circuit, it has the units of Ohms. You will experimentally show that the impedance of a capacitor decreases as frequency increases.

Apparatus

Digital Oscilloscope, HP Function Generator, 0.02-0.03µf Capacitor, and 10kΩ Resistor.

Introduction

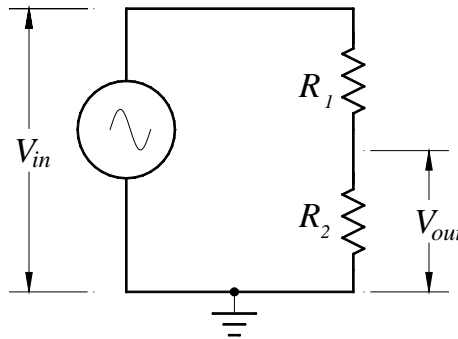


Figure 1 Schematic diagram of a voltage divider.

Before starting to analyze circuits containing capacitors it will be useful to look at a circuit called a **voltage divider**. A voltage divider (see Figure 1) is just two resistors connected in series. The voltage across the second resistor R_2 is called the output voltage, V_{out} . The input voltage, V_{in} must equal the sum of the voltages across the two resistors

$$V_{in} = V_{R_1} + V_{R_2} = IR_1 + IR_2. \quad (1)$$

The ratio of the output voltage to the input voltage is given by

$$\frac{V_{out}}{V_{in}} = \frac{IR_2}{IR_1 + IR_2} = \frac{R_2}{R_1 + R_2}. \quad (2)$$

This equation is valid for DC voltages ($V_{in} = \text{a constant}$) or AC voltages ($V_{in} = A \sin \omega t$). Notice that, in the AC case, the amplitude of the output voltage would be constant and independent of the angular frequency (ω) of the input voltage. If you were to now replace the resistor R_2 with a capacitor (See Figure 2), the behavior of this circuit would change dramatically. The first thing you might notice is that the magnitude of the output voltage is no longer constant as the frequency changes. Another thing you might notice is that the amplitudes of the voltages do **not** add linearly according to Kirchoff's Loop Theorem

$$V_{in} \neq V_R + V_C. \quad (3)$$

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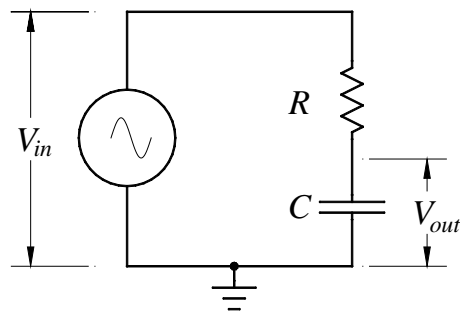


Figure 2 Schematic of a "capacitive" voltage divider.

With a little investigating you would find that the sum of the squares of the voltage amplitudes must be used

$$V_{in}^2 = V_R^2 + V_C^2. \quad (4)$$

Equation 4 looks like the Pythagorean Theorem. The voltage across the resistor is acting as if it is at a "right angle" to the voltage on the capacitor! This behavior of changing the *phase* of the voltage is called *reactance*. The relationship between these three voltages leads to the *phasor diagram* shown in Figure 3. The voltage across the resistor is represented by a vector drawn on the *x*-axis, the voltage across the capacitor by a vector along the *y*-axis, and the input voltage is a vector along the hypotenuse. (Although the magnitudes of V_R and V_C are the same in Figure 3, this is not always the case.)

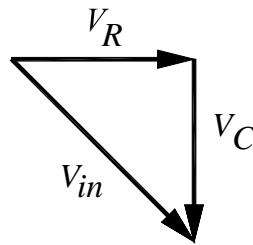


Figure 3 Phasor diagram. The lengths of the vectors represent the amplitudes of the voltages in the circuit. The directions of the vectors represent the relative phases of the voltages.

The *impedance* of the capacitor, X_C , (which is analogous to resistance) determines the current flow through a capacitor. Impedance is measured in Ohms. The impedance of a capacitor is inversely proportional to angular frequency and is given by

$$X_C = - \frac{1}{\omega C}. \quad (5)$$

Where C is the capacitance in farads. Notice that for DC voltages the impedance is infinity and no current flows. (*Aside:* This is how the AC coupling switch on the oscilloscope works --it subtracts away the DC voltage by switching in a capacitor in series with the input.) As frequency increases the impedance decreases so the capacitor conducts more current. Starting with Equation 4 you should see that the ratio of the output voltage squared to the input voltage squared is given by

$$\frac{V_{out}^2}{V_{in}^2} = \frac{V_C^2}{V_C^2 + V_R^2} = \frac{IX_C^2}{IX_C^2 + IR^2} = \frac{X_C^2}{X_C^2 + R^2}.$$

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Substituting in for the impedance for the capacitor from equation 5 the ratio becomes

$$\frac{V_{out}}{V_{in}} = \frac{(1/(wC))^2}{(1/(wC))^2 + R^2} \quad (6)$$

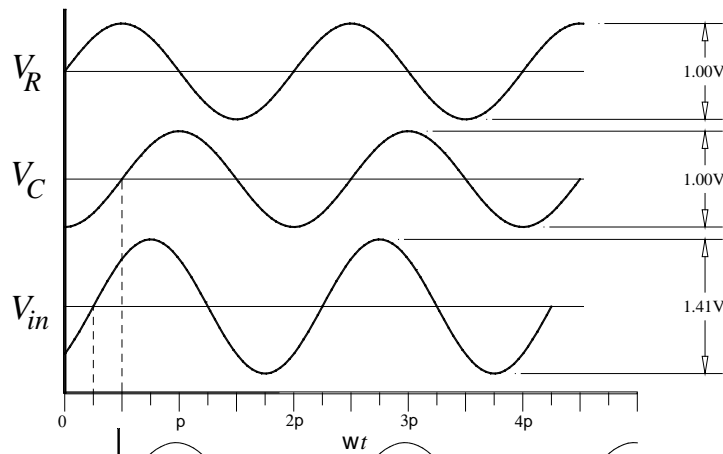


Figure 4 Plot showing the phase relationship between voltages in an RC circuit.

The way the capacitor makes its voltage appear at "right angles" to the voltage on the resistor is by shifting the **phase** of its voltage by 90° relative to the resistor. The phase is simply an angular constant added or subtracted from the $\sin(wt)$ waveform. One way of looking at the phase is thinking of it as changing the time when the waveform starts looking like a sine wave starting at the origin. Figure 4 is a graph of the voltage on the resistor ($V_R = 0.5\sin(wt)$); the voltage on the capacitor ($V_C = 0.5\sin(wt - 90^\circ)$), and the input voltage ($V_{in} = 0.705\sin(wt - 45^\circ)$) as a function of time multiplied by angular frequency. Notice that the voltage across the capacitor is shifted by -90° relative to the voltage across the resistor. Recall that $w = 2\pi f = 2\pi/T$ (where w is the angular frequency). So angular frequency multiplied by time is an angle.

QUESTION 1 - Look closely at Figures 3 and 4. What is the phase difference between V_{in} and V_R for these drawings?

Frequency Behavior of an RC Circuit

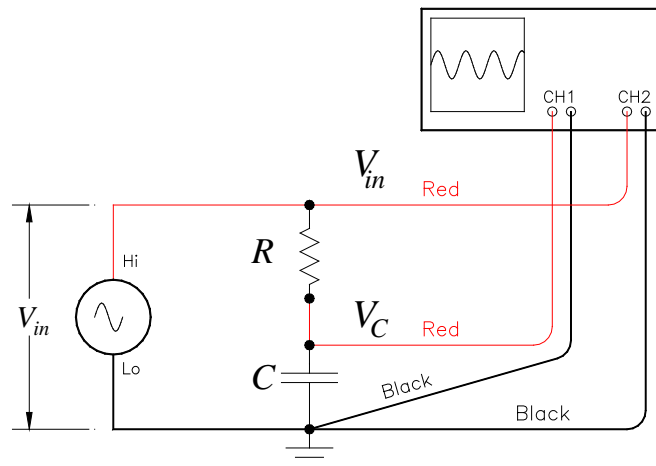


Figure 5 Wiring diagram showing how to connect both channels of the oscilloscope.

1) Connect the 10kΩ resistor and the capacitor in series with the function generator as shown in Figure 5. Turn on the oscilloscope and set it to display both CH1 and CH2. Check that Probe is set

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to 1X, the Volts/Div is 1.00, and the DC level is set to zero on both CH1 and CH2 of the oscilloscope. Activate the Trigger menu and set the trigger Source to CH2 the Slope can be Rising or Falling, Mode should be Normal, the Coupling DC, and the level should be about 0.0V. Set the function generator to make a sine wave of $8.0V_{pp}$ with no DC-offset. (8.0 divisions on the 1.0 Volt scale.) Connect the oscilloscope to measure V_{in} on CH2 and V_{out} on CH1. Vary the frequency of the function generator from about 100Hz to 10kHz and watch what happens to V_{in} and V_{out} . Go through this step quickly to get a feeling for what is happening to the voltages as frequency varies.

QUESTION 2 - Discuss what you observe happen to V_{in} and V_{out} . as the frequency goes from low to high.

2) Make a data table with columns for frequency f , V_{in} , Div, Volts/Div, V_C , Div, Volts/Div, and V_R . Using the Measure menu, set up the oscilloscope to measure the frequency on CH2 and the Volts peak-to-peak on CH1 and CH2. Set the frequency of the function generator to 100Hz, adjust the amplitude on the function generator until V_{in} (CH2) is 8.00V. Record the voltage on the capacitor V_C .(CH1) and the frequency from the oscilloscope Text Menu windows. To measure the voltage on the resistor you need to swap the place of resistor and capacitor. This can be easily accomplished by swapping the function generator and CH2 leads with the ground leads. See Figure 6. Record the voltage across the resistor V_R . (CH1) Remember that the oscilloscope only measures voltages with respect to the potential source of ground. Whichever component has one side connected to ground determines the voltage you are measuring. (This is analogous to how your measured the voltages on the two resistors in *Introduction to the Digital Oscilloscope*.) Also you may need to change the Volts/Div to get an amplitude of $> 3.3Div$ so that the Measure function can accurately record the amplitude.

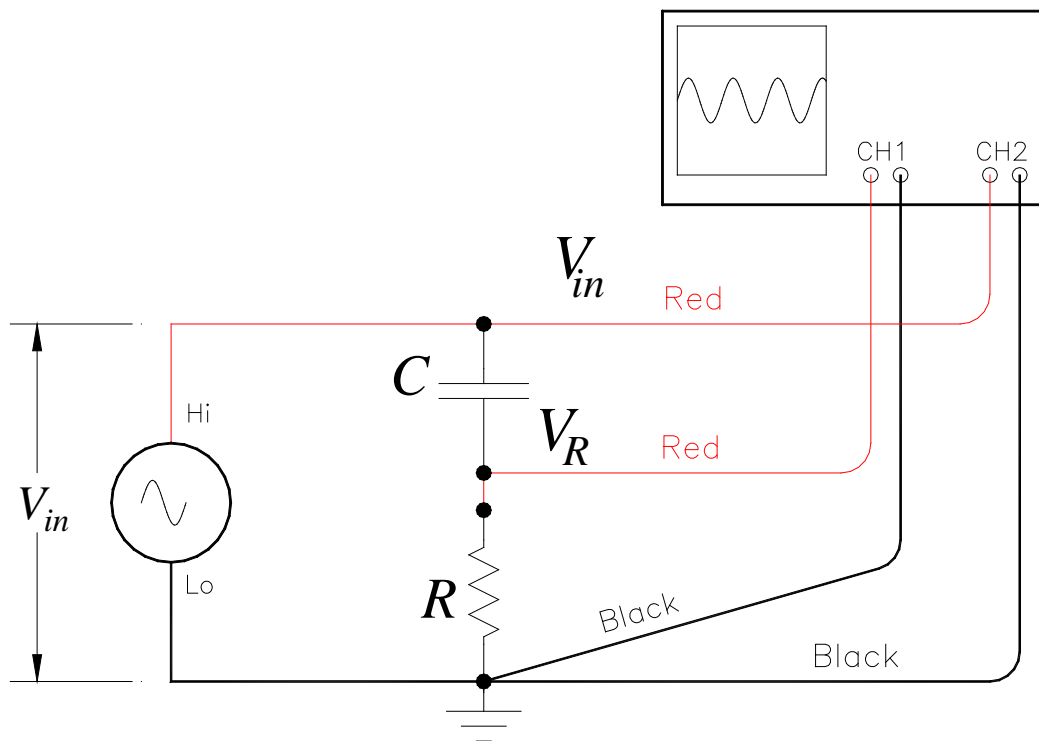


Figure 6 Wiring diagram showing how to swap the places of R and C to measure V_R .

Record the frequency and voltages for V_{in} , V_C , and V_R for the function generator frequencies 200, 300, 400, 500, 600, 650 700, 750, 800, 900, 1000, 1500, 2500, 4000, 5000, and 10,000 Hz. Because the "load" on the function generator gets smaller as the frequency increases

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the output decreases slightly. To make your analysis easier you should adjust the amplitude knob on the function generator to keep $V_{in} = 8.00V$ each time you change the frequency on the function generator.

Analysis

3) Use Excel to do your analysis. Make columns for f , V_{in} , V_C , and V_R and enter your data. Make two more columns to calculate $V_C + V_R$ and $(V_C)^2 + (V_R)^2$.

QUESTION 3 - If $V_{in} = 8.0 \pm 0.2V$, what is the uncertainty in $V_C + V_R$ and $(V_C)^2 + (V_R)^2$?

4) Look at your values for the sums of the voltage on the capacitor and resistor and the sums of the square of these voltages.

QUESTION 4- Do the voltages appear to add linearly (as in Eq. 3) or in quadrature (as in Eq. 4)? Justify your answer with numerical evidence.

5) Add two more columns to your spreadsheet to calculate the ratio $(V_C/V_{in})^2$ and the theoretical value given by Eq. 6 as a function of frequency. Use the R and C values written on the components blocks for calculations in Eq. 6. In Excel $\pi = \text{pi}()$. Make a graph plotting your data $(V_C/V_{in})^2$ with symbols only, and the theoretical value Eq. 6 with a smooth line only, as a function of frequency. Print a copy of this graph and spreadsheet for your report.

6) Look at your graph of the ratio $(V_{out}/V_{in})^2$ as a function of frequency.

QUESTION 5 - Does the behavior of this graph seem to be described by Equation 6?

7) Make a "zoomed in plot" of the region where $(V_{out}/V_{in})^2$ is equal to 0.5. Print a copy of this graph to turn in with your report. On this graph sketch a smooth line connecting your experimental data points. From this sketched line determine the experimental frequency where $(V_{out}/V_{in})^2$ is equal to 0.5. Using the values for the resistor and capacitor that you used, calculate f_c using the following relation derived from Equation 6

$$f_c = \frac{1}{2\pi RC} \quad (7)$$

QUESTION 6 - Compare your experimental value and calculated value for f_c . Don't forget to estimate uncertainties in these values for the comparison.

References

Haliday, Resnick, and Walker, *Fundamentals of Physics 7th Ed*, Sections 31-6 & 31-8 (Pages 835-842)

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Experiment 9- Build a Radio

In this lab you will investigate the behavior of a resonant circuit using a capacitor and inductor. The resonant frequency of the circuit you build will be adjustable over the frequency range of the AM radio band. With the addition of an antenna, a germanium diode, and a simple low pass filter you will be able to tune your circuit to hear radio waves using a computer speaker.

Apparatus

Digital Oscilloscope, HP Function Generator, 100pf variable capacitor, 1mH inductor with ferrite core, germanium diode, 0.01uf capacitor, and 10kWresistor.

Introduction

A child sitting on a swing pumps their legs rhythmically and gradually swings higher and higher. A wine glass sitting in front of a loudspeaker that is emitting a sound of just the right frequency develops a very large amplitude of vibration and eventually shatters. The Tacoma Narrows Bridge, blown by strong wind manages to push the bridges steel girders back and forth at just the right frequency, builds up a wild oscillation, and comes crashing down. These are all examples of *resonance* phenomena, where a large amplitude vibration develops when a relatively small driving force is applied at a frequency that matches the resonant frequency of the system. For example, in the case of the child on the swing, if the child swings their legs just at the bottom of the swing, the resulting amplitude will get bigger. If the child swings their legs at a frequency faster or slower than the natural frequency of the swing, the amplitude will die down. Note that in the cases described above there is relatively little friction or *damping* in the system. This means that energy deposited in the system by the driving force will remain in the system for a long time, enabling a large amplitude oscillation to build up over many cycles of the motion.

The phenomenon of resonance plays a critical role in the operation of the radio you will build today. Radio signals from distant transmitters will induce currents in an antenna, but these currents are usually unbelievably small. By coupling the antenna to a tuned resonant circuit, these minute currents will be able to induce a much larger oscillation in the resonant circuit, in much the same way that the oscillations in the mechanical examples above develop.

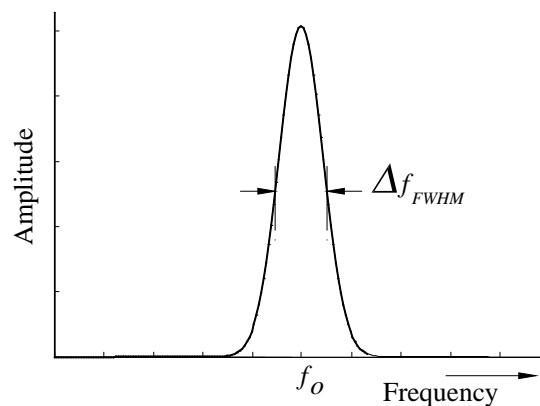


Figure 1 *Amplitude of oscillation as a function of driving frequency for a resonant system.*

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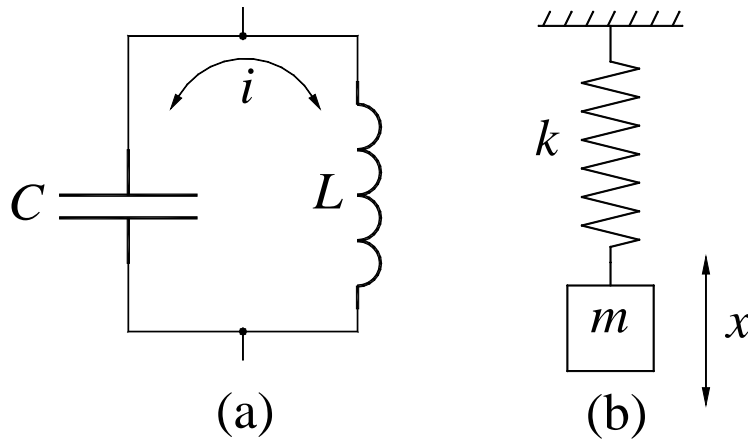


Figure 2a) Simple LC Circuit. **b)** Mass on a spring.

An **inductor** (which is a coil of wire and whose electrical properties are described more below) and capacitor connected in parallel (an *LC* circuit), such as the one shown in Figure 2a, has such a resonance frequency, f_o . In addition to allowing a large amplitude oscillation to develop, a resonant *LC* circuit is also selective to which frequencies it responds to; only a narrow range of driving frequencies near f_o will cause much of a response. By varying the value of f_o you will be able to **tune** to different radio stations. The width of the resonance curve can be characterized by measuring its “full width at half maximum,” which is labeled D_{FWHM} in Figure 1.

To find the resonance frequency f_o apply Kirchoff’s Loop Law to the *LC* circuit shown in Figure 2a. The only elements of the loop are the inductor, L , and the capacitor, C ; therefore, the sum of these voltages must equal zero

$$V_L + V_C = 0.$$

You already know that the voltage drop across a capacitor is

$$V_C = \frac{q}{C}.$$

The characteristic voltage drop across an inductor is given by

$$V_L = L \frac{dI}{dt}$$

where L is the **inductance** of the coil measured in *Henries*. From the above you should see that the defining property of an inductor is that the voltage drop across them is proportional to the the derivative of the current flowing into them.

Plugging these expressions into Kirchoff’s Loop Law results in

$$L \frac{dI}{dt} + \frac{q}{C} = 0.$$

Since current is the change of charge with time, $I = \frac{dq}{dt}$, the above equation can be rewritten as

$$\frac{d^2q}{dt^2} + \frac{1}{LC}q = 0 \tag{1}$$

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Do you recognize this form of equation? It is mathematically identical to the equation of motion for a mass on a spring! See Figure 2b. Recall that for a mass m and an ideal spring with a spring constant of k

$$\frac{d^2x}{dt^2} + \frac{k}{m}x = 0. \quad (2)$$

Notice that equations (1) and (2) are mathematically identical. For the mass-spring system the natural frequency of oscillation is given by

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}},$$

therefore, we can conclude that the natural frequency of oscillation for the LC circuit is given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \quad (3)$$

where the inductance, L , is measured in Henrys and the capacitance, C , in Farads.

Q-factor

Another important aspect of the frequency response curve shown in Figure 1 is the “sharpness” of the peak. The sharper the peak is higher the **quality factor** or Q is. The quality factor is quantified by the width of the resonance curve, Δf_{FWHM} , measured at the point where the amplitude drops by the square root of two relative to the resonant frequency

$$Q \gg \sqrt{2} \frac{f_0}{\Delta f_{FWHM}}. \quad (4)$$

Figure 3 shows two frequency response curves for ideal oscillators having different values of Q . When you build your radio you will want the Q of your LC circuit large so that the tiny currents from the antenna can build to large amplitudes in the LC circuit. A large Q will not only get you bigger amplitudes of oscillation (and hence greater sensitivity) but also, you will have greater selectivity because the range of frequencies for resonance will be smaller. A small Δf_{FWHM} is important if you only want to listen to one station at a time.

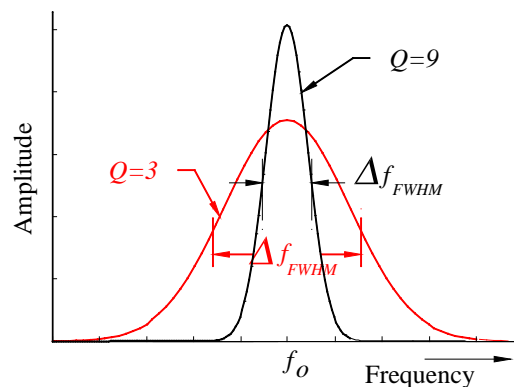


Figure 3 Amplitude as a function of frequency for two systems with different Quality factors.

AM Radio

The radio you will build is designed to receive AM broadcasts, which stands for **amplitude modulation**. Even though this technique represents only one of many possible ways to transmit information wirelessly, many of the basic principles used in your radio underlie all

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radio, TV, and optical communications. AM transmission makes use of a radio frequency (rf) signal in the band between 530 kHz and 1600 kHz. The resonant LC circuit in your radio receiver is tuned to respond to signals in this frequency range or **band**. Figure 4 shows an example of a radio signal of amplitude, A_0 , and frequency, f_c , of the form

$$V(t) = A_0 \cos(2\pi f_c t). \quad (5)$$

This signal is referred to as the **carrier wave** and the frequency, f_c , as the **carrier frequency**, which is assumed to lie somewhere in the AM broadcast band. There is not yet any audio information encoded in this signal.

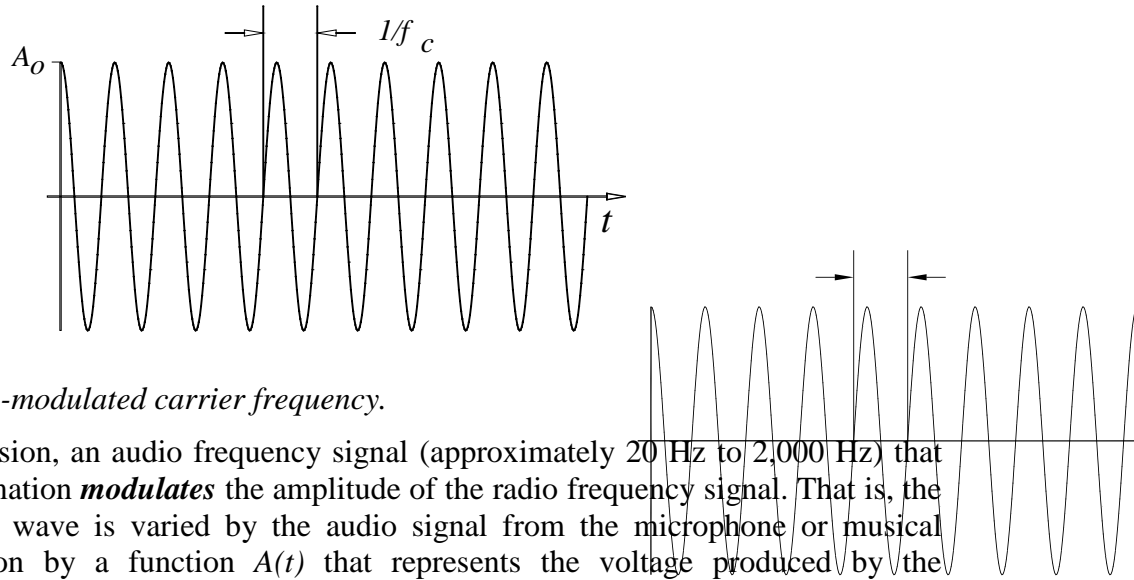


Figure 4 Plot of raw un-modulated carrier frequency.

In AM transmission, an audio frequency signal (approximately 20 Hz to 2,000 Hz) that carries the sound information **modulates** the amplitude of the radio frequency signal. That is, the amplitude of the radio wave is varied by the audio signal from the microphone or musical recording in the station by a function $A(t)$ that represents the voltage produced by the microphone as a function of time. See Figure 5.

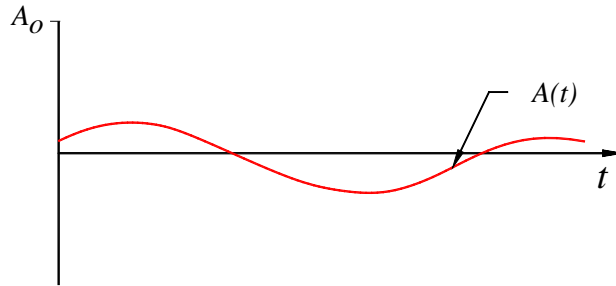


Figure 5 Segment of a sound signal.

In order to transmit this audio signal the broadcast station will radiate an electromagnetic wave of the form:

$$V(t) = (A_0 + A(t))\cos(2\pi f_c t) \quad (6)$$

The transmitted signal, an amplitude modulated radio signal, is shown in Figure 6. Note how the sound signal forms an **envelope** around the carrier frequency signal as it changes amplitude with time.

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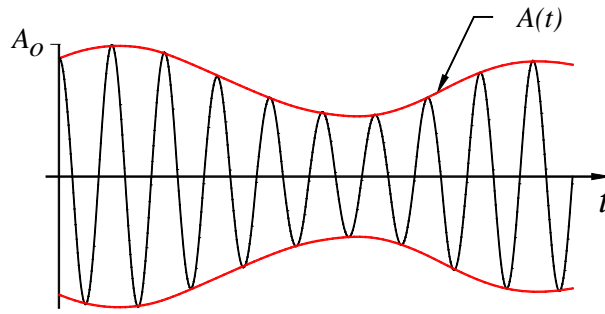


Figure 6 Amplitude modulated signal. $V(t) = (A_o + A(t))\cos(2\pi f_c t)$

For a radio to produce sound that is similar to the sound that was spoken into the microphone at the radio station it must be able to:

1. **Select** the desired frequency (radio station) by using a tuned resonant circuit. This is accomplished by adjusting the resonant frequency of the LC circuit.
2. **Extract** the audio signal from the amplitude modulated radio signal. This involves using a diode to rectify the radio signal, making the signal's average value non-zero.
3. **Filter** the remaining radio frequency part of the signal through a low-pass filter, so that only the audio signal $A(t)$ remains.

Extraction

Suppose a sine wave signal provided by a signal generator is fed into a diode, as shown in Figure 7. Recall that due to the diode's one-way behavior to conduct current, only the positive portions of the signal will appear on the oscilloscope.

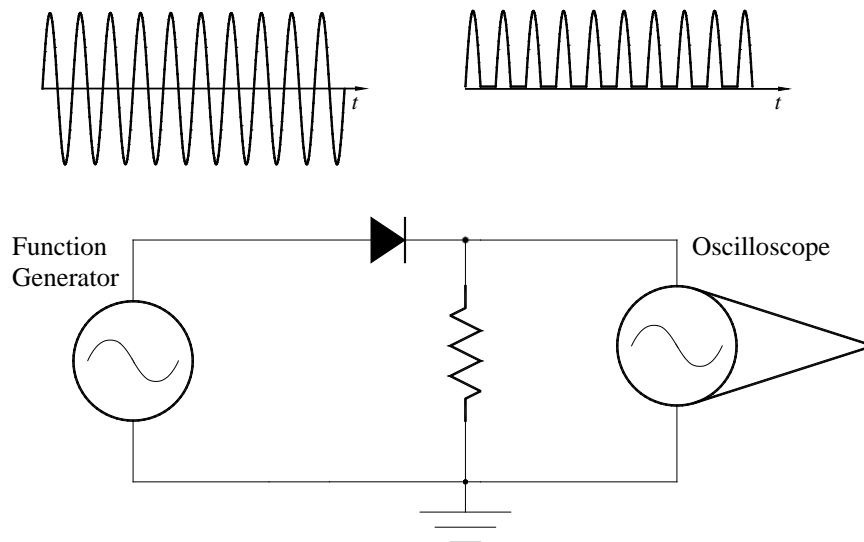


Figure 7 Diagram showing how a diode cuts off the negative part of an AC wave.

Therefore, if the radio signal shown in Figure 6 is connected to the circuit in Figure 7 the **rectified** radio signal of our example will look like Figure 8.

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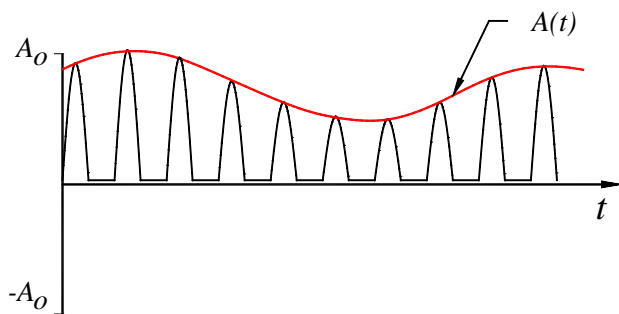


Figure 8 Rectified radio signal.

Low pass filter

Now that the signal has been rectified, the next step in recovering the audio signal is to eliminate the radio frequency “wiggles” from the carrier wave. This is accomplished by adding a *low pass filter* based on a simple *RC* circuit as shown in Figure 9 which limits the range of frequencies to only the audio range.

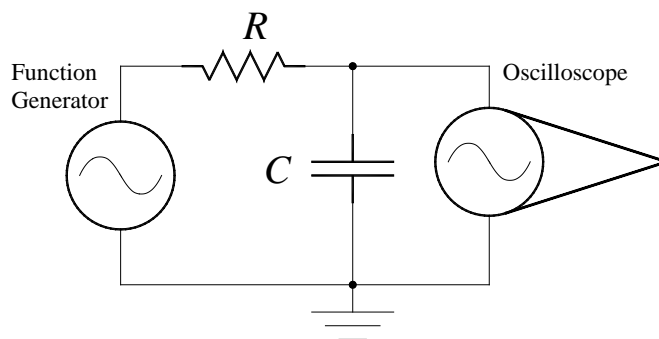


Figure 9 Schematic diagram of a simple *RC* Low-Pass Filter.

Suppose a sine wave of amplitude, V_{in} , and frequency, f , (and corresponding period $1/f$) is fed into the *RC* circuit shown in Figure 9. If the period of the sine wave is long compared to the *RC* time constant then we expect that the amount of charge on the capacitor (and hence the voltage across the capacitor) will fluctuate significantly. (The situation is analogous to the case of a small bathtub connected by a wide pipe to a reservoir whose height is slowly rising and falling. In this case we expect that the level of the water in the tub will easily be able to follow the changes in the height of the reservoir.) Thus at sufficiently low frequencies the voltage fluctuations generated by the signal generator pass through to the capacitor un-attenuated.

On the other hand, suppose the period of the sine wave is short compared to the *RC* time constant. In this case we expect that the amount of charge on the capacitor (and hence the voltage across the capacitor) will **not** have time to fluctuate significantly. (Now the situation is analogous to the case of a large bathtub connected by a narrow pipe to a reservoir whose height is rapidly rising and falling. In this case we expect that the level of the water in the tub will not be able to respond much to the rapid changes in the height of the reservoir. Rather, we expect the water level in the tub to hover near the average height of the reservoir.) Thus, at sufficiently high frequencies, the voltage fluctuations generated by the signal generator do not “pass through” to the capacitor.

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More quantitatively, it can be shown that if a sine wave of amplitude V_{in} and frequency f passed into the RC circuit, the amplitude of the ratio of output signal V_{out}/V_{in} is given by

$$\frac{V_{out}}{V_{in}} = \sqrt{\frac{X_C^2}{X_C^2 + R^2}} \quad (7)$$

where X_C is given by

$$X_C = \frac{1}{2\pi f C}.$$

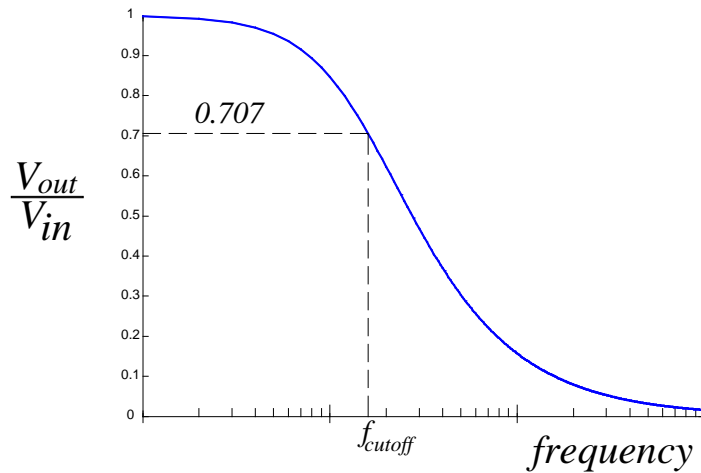


Figure 10 Semi log plot of low pass filter response as a function of frequency. Notice that the plot covers three decades of frequency range.

Here the *cutoff frequency* is defined by

$$f_{cutoff} = \frac{1}{2\pi RC}.$$

Notice that when the frequency f is much less than f_{cutoff} then V_{out} is approximately equal to V_{in} . On the other hand when f is much greater than f_{cutoff} then V_{out} is essentially zero. Finally observe that when the frequency equals f_{cutoff}

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{2}} \approx 0.707.$$

The RC circuit behaves as a **low pass filter**, passing unaltered those frequencies that are well below the cutoff frequency while strongly attenuating those frequencies that are well above the cutoff frequency. If the rectified radio signal is passed through a low pass filter whose cutoff frequency is well below the carrier frequency ($\gg 850\text{kHz}$) but well above all audio frequencies ($\gg 10\text{Hz}$) then the rf “wiggles” should be filtered out while the audio oscillations should pass through unaffected. The signal that emerges from the low pass filter, shown in Figure 11, is a replica of the original audio signal, $A(t)$, riding on a dc offset, A_o .

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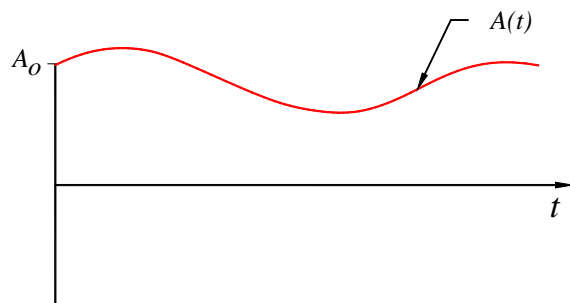


Figure 11 Diagram of the extracted sound signal.

Procedure

Your goal for today is to first observe that the LC circuit supplied acts as a resonator with a resonant frequency in the range of the AM radio band, 530-1620kHz. You then will measure the Q of this circuit. Finally you will construct a radio by adding a germanium diode to rectify the output of the LC circuit, filter this with a low pass filter and listen to the sound with a computer speaker.

Observe Changing the Capacitor Changes the Resonance Frequency

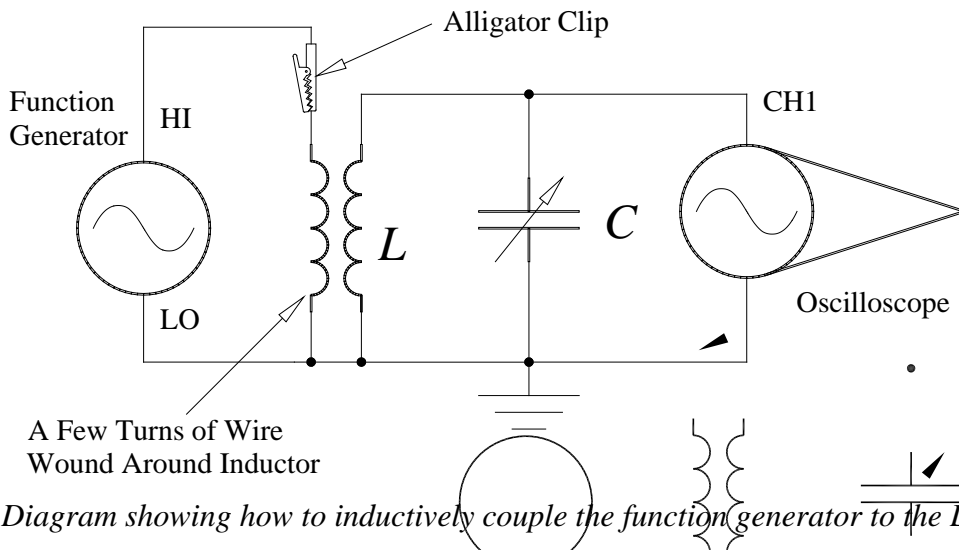


Figure 12 Diagram showing how to inductively couple the function generator to the LC circuit.

- 1) One of the component blocks contains a coil with a ferrite core connected to a variable capacitor. A small wire is wrapped around the coil. Connect the function output (600W) of the HP function generator to the bare end of this wire through the *alligator clip*. Note that one end is marked as ground and this end must be connected to the LO side of the function generator. The small wire *inductively couples* the function generator to the coil as shown in Figure 12. Turn the knob on the capacitor until it is fully **counter-clockwise**. Set the frequency of the function generator to 100kHz and the amplitude knob about in the middle of the range. The DC offset knob should be set to zero.
- 2) Connect the CH1 input of the oscilloscope to the LC circuit. See Figure 12. Make sure that the CH1 Probe is set to 1X and that the Trigger Source is set to CH1 and the Mode is Auto. Using the Measure Menu set up the oscilloscope to display the frequency on CH1 and the V_{pp} on CH1.

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3) Slowly adjust the frequency of the function generator between about 100kHz and 1000kHz and record the behavior of the circuit.

QUESTION 1 - Describe whether or not the circuit behaves as indicated by Figure 1?

4) Adjust the frequency of the function generator until the amplitude of the oscillation is a maximum. Record the voltage and frequency indicated on the oscilloscope and the function generator.

5) Now vary the value of the capacitor by turning the knob about 1/4 turn clockwise and repeat step 4). Adjust the value of the capacitor again, by turning the knob another 1/4. Repeat the above measurement.

QUESTION 2 - Which adjustment position of the capacitor makes the value of capacitance (C) a maximum, fully CCW or fully CW? Justify your response using Equation 3 and your above observations.

Set your tunable capacitor so it is adjusted to its maximum value.

Measure the Resonance and Q-factor of your LC circuit.

6) Your goal here is to make a smooth graph of the frequency response of the *LC* circuit. Set the function generator to 100kHz and leave the amplitude knob about mid-scale. Make a data table with columns for Frequency, Volts/ Div, and Volts. Measure the peak-to-peak amplitude of the wave across the *LC* circuit as shown in Figure 12. Record the Frequency from the oscilloscope, Volts/Div, the number of Divisions, and the amplitude in Volts.

7) Increase the frequency of the function generator by about 100kHz. Record the frequency and peak to peak amplitude. Continue increasing the frequency and recording data until you get to the maximum value or resonance. Note that as you get near resonance the voltage will very rapidly increase so you will need to change the frequency by smaller amounts, sometimes as small as 0.02 division! For a nice smooth curve you should have about 8 to 10 points leading up to resonance. You can always go back and fill in data points.

8) After the resonance, continue increasing the frequency of the function generator and recording the amplitude until you get to 1000kHz.

9) Using Excel, make a graph of Voltage as a function of frequency from 0 to 1000kHz. Plot the data as points with a smooth curve through your points. Print a copy of this for your report.

10) Now change the scales on the x-axis to zoom in on the resonance peak, a range of about 200kHz should be fine. Print a copy of this graph for your report. On this graph measure the frequency range of the peak at half max, Δf_{FWHM} . See Figure 3.

QUESTION 3 - What is the Q-factor of your circuit using Equation 4?

EXPERIMENT 9

Add a Diode to Rectify the Audio Signal

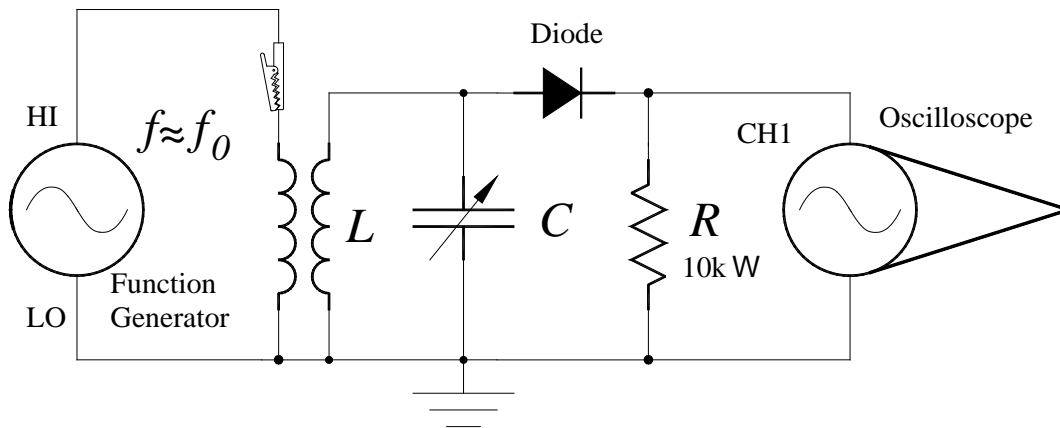


Figure 13 Schematic diagram of radio receiver circuit using a function generator as frequency source.

11) Add the diode and a resistor detector to the LC circuit, as shown in Figure 13. Adjust the frequency of the function generator to be close to the resonant frequency of your LC combination. Use the oscilloscope to observe the signal “before” and “after” the diode. Make a sketch of what you observe for your report.

QUESTION 4 - Discuss in each case if the signals appear the way you expect.

Low pass filter

12) Make a low-pass filter by adding a capacitor as shown in Figure 14.

QUESTION 5 - Calculate and report the value of the cutoff frequency for this design.

Turn the amplitude knob on the function generator up and down. (Make sure the oscilloscope coupling is on DC!)

QUESTION 6 Describe what you observe on the oscilloscope.

13) Now remove the diode from the circuit and rotate the amplitude knob on the function generator up and down. Try this with the Sec/Div set to 1Sec/Div.

QUESTION 7 - Describe what happens. Explain why the output voltage behaves as it does with and without the diode.

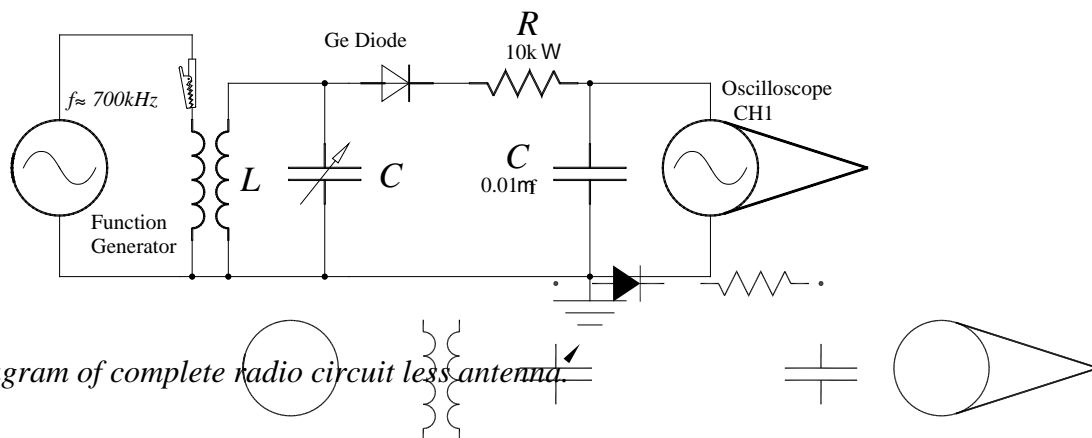


Figure 14 Diagram of complete radio circuit less antenna.

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Remove Function Generator and Add the Antenna

14) Disconnect your circuit from the function generator and oscilloscope by removing all leads attached to your circuit. Leave the rest of the circuit assembled. Please be careful not to drop the ferrite core out of the inductor as it will break. Take your radio to the lab bench with the antenna feed and plug in the amplified speaker from a PC to your circuit as shown in the Figure 15.

QUESTION 8 - Can you now tune your radio to different stations?

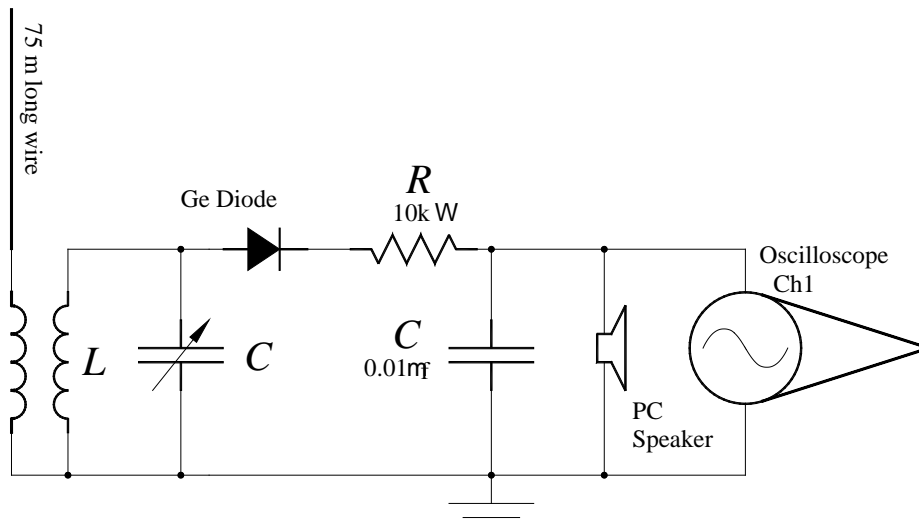


Figure 15 Complete Diagram of a radio with antenna and amplified speaker.

QUESTION 9 - The frequency spacing between stations in the AM band is 10 kHz , Are the range of frequencies, Δf_{FWHM} allowed through your circuit consistent with this frequency spacing? In other words, if there was a station broadcasting at 540 kHz and one on 550 kHz could you tune your radio so that you only heard only one station?

QUESTION 10 - Imagine a very good LC circuit where the Q was on the order of $10,000$. What would the **bandpass**, Δf_{FWHM} , be at 1000 kHz ?

QUESTION 11- Would a radio with the above bandpass make a desirable radio receiver? Explain your answer.

References

Haliday, Resnick, and Walker, *Fundamentals of Physics 7th Ed*, Chapter 31 (Pages 826-851)

Physics 106 Laboratory Manual Spring 2005, RC Circuits and AC Circuits.

EXPERIMENT 9

Experiment 10 – Induced Voltages

In this experiment you will qualitatively evaluate Faraday's Law of Induction. You will use your understanding of the magnetic field from a bar magnet and the motion of the magnet to determine the change in the magnetic field applied to a coil of wire. A galvanometer will be used to measure the direction of the induced current in the coil. Using the Right Hand Rule you will then determine the direction of the induced magnetic field. You will test Lenz's Law, which predicts that the change in the applied magnetic field and the induced magnetic field always oppose each other.

Apparatus

Digital oscilloscope, 2, 10, and 20 turn coils, a bar magnet, small magnetic compass, galvanometer, banana leads, soft iron rod, telegraph switch, and AA batteries.

Introduction

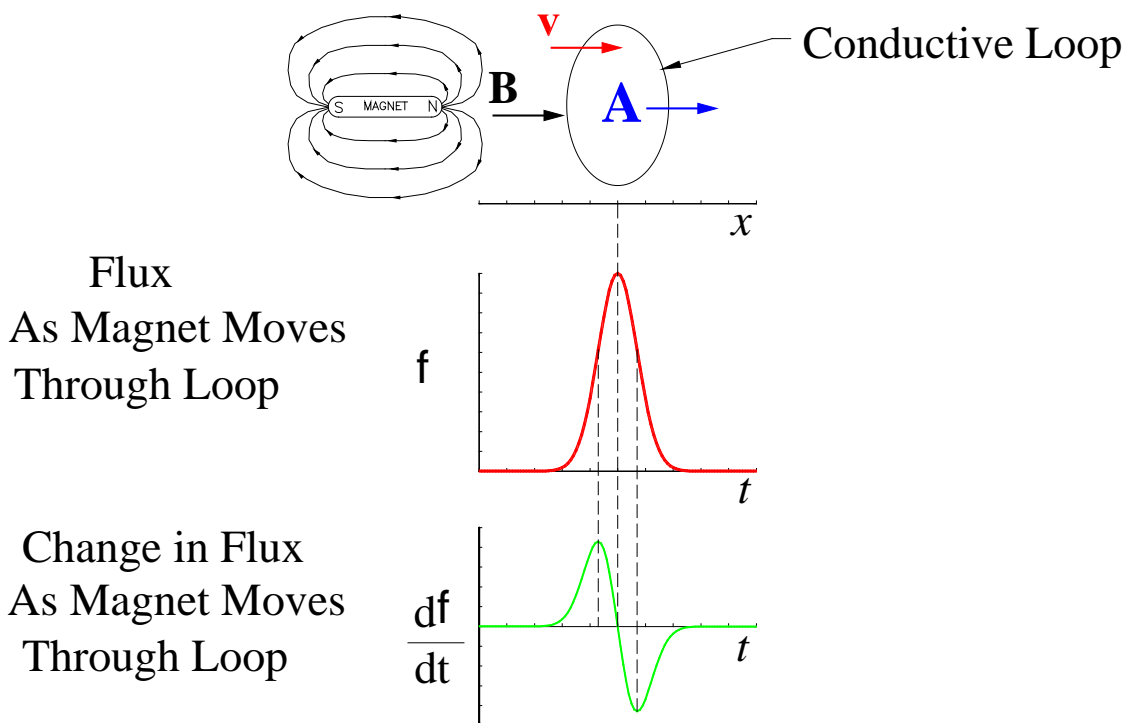


Figure 1 Diagram showing the flux as a magnet moves through a coil of wire.

In 1820 Hans Christian Oersted discovered that a wire carrying an electric current had a magnetic field surrounding it. In 1831 Michael Faraday discovered that a magnetic field that is changing with time will induce a voltage and current in a nearby coil of wire. It was already known that a current carrying wire had a magnetic field surrounding it, and Faraday's discovery showed that the reverse was also possible if the magnetic field was changing with time. Figure 1 is a diagram showing how the effect is observed. A bar magnet is moved toward a coil of wire that is connected to an oscilloscope. In the figure the magnetic field lines start at the north pole of the magnet and end on the south pole. The direction of the magnetic field is determined by the direction of force that a small "north pole" would experience if it were placed in the field. In Figure 1 the north end of the magnet is moved at constant velocity into a coil. As the magnet moves closer to the coil the "flux", or the number of field lines per unit area, will increase in the

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coil until the middle of the magnet is in the center of the coil. At this point all of the field lines from the magnet will be parallel to the area vector \mathbf{A} of the coil which makes the flux a maximum. At this point the flux slowly decreases to zero as the magnet travels through the coil.

To understand what flux is, consider a surface bounded by a closed conducting loop. The number of magnetic field lines passing through that surface is the magnetic flux f , where f is defined as

$$f = \oint \mathbf{B} \cdot d\mathbf{A} \quad (1)$$

If the magnetic field \mathbf{B} and the area of the coil are constant, the above integral reduces to just the dot product of the magnetic field and the area of the coil, i.e. $f = \mathbf{B} \cdot \mathbf{A}$. Notice that the sign of the flux depends on the direction of \mathbf{B} relative to \mathbf{A} .

The bottom line to all of this is if \mathbf{A} is parallel to \mathbf{B} the magnitude of the flux is a maximum. The sign is determined by the directions of \mathbf{A} to \mathbf{B} . This explains why the flux is a maximum in Figure 1 when the magnet is centered in the coil.

QUESTION 1 - What would happen to the flux if the magnet were turned around 180°?

If \mathbf{A} is perpendicular to \mathbf{B} then the flux is zero. The flux can also be zero if the magnitude of the magnetic field goes to zero. This explains why the flux from the magnet is zero as it is far away from the coil in Figure 1.

Faraday's Law of Induction states that

The change in magnetic flux f in a coil of N turns of wire will induce in the wire a voltage V directly proportional to the time rate of change of the magnetic flux

$$V = -N \frac{df}{dt} \gg -N \frac{Df}{Dt} \quad (2)$$

Study the graph of the flux and the change in flux with time in Figure 1. Notice how the change in flux is positive as the magnet enters the coil and is negative as the magnet travels through leaving the coil. These two curves can be duplicated by quickly pushing the magnet into the coil to its midpoint and then quickly withdrawing it.

According to Faraday's Law the larger the number of turns in the coil, the larger will be the induced voltage. Also the faster the flux is changed, the larger will be the induced voltage. You will investigate both of these behaviors in today's lab. The negative sign in Equation 2 is important because it indicates that the induced voltage is of such a polarity that it opposes the change in the magnetic flux in the coil. If this were not true, it would be possible to devise a perpetual motion machine based on magnetic induced voltages. ***Lenz's Law*** formalizes this idea and states:

The magnetically induced voltage produces a current that results in a magnetic field that opposes the change in the original magnetic field.

Procedure

This experiment has four major parts. In each part you will do something to change the flux in a coil of wire, i.e. change the amount or the direction of magnetic field passing through the coil of wire. Based on what you know about the initial and final magnitudes and directions of this ***applied*** magnetic field, you will determine the direction of the CHANGE in the applied magnetic field. In the first part of the experiment you will let a magnet fall through a coil and

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observe the induced voltage as a function of time. From this you can deduce how the flux changes as a magnet passes through it. In the other three parts you will use magnet held in your hand to create a change in the direction of the magnetic field in a coil of wire. This change in the applied field creates an *induced* current. A galvanometer connected to the coil lets you determine the direction of the induced current flowing in the coil. From the direction of the current, you will deduce the direction of the induced magnetic field using the *right hand rule*.

You should observe in all cases that the induced field opposes the CHANGE in the applied field. It is difficult to collect exact numerical data with the apparatus available for this experiment, so your investigations will be qualitative, but rigorous. At each step along the way you must make an unambiguous sketch of the system being investigated and provide a complete and clearly written description of what you did and observed.

The Voltage Induced By a Moving Magnet

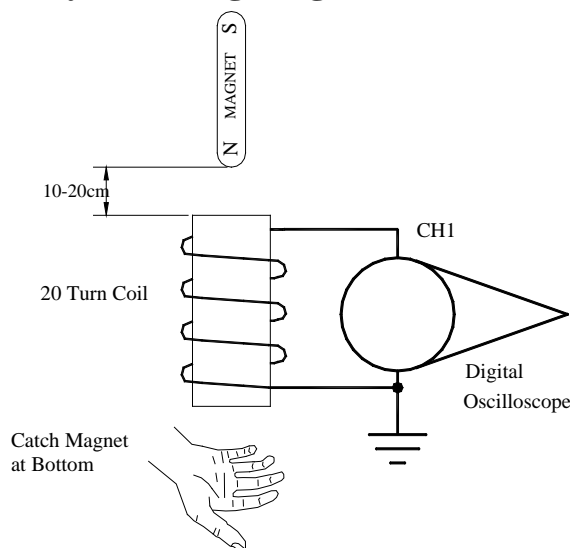


Figure 2 - Diagram showing circuit to measure induced voltage in a coil as a magnet falls through it.

- 1) Determine which end of your magnet is a north pole. You can use a compass to find which end of your magnet is a south pole since the end of the compass which points north is defined as a north pole. (This means that the earth's geographic north pole is actually a magnetic south pole.) The end of your bar magnet that the compass points to is therefore a south pole.
- 2) Connect the 20 turn coil to the digital oscilloscope as shown in Figure 2. Set the oscilloscope to display only CH1. Check that Probe is set to 1X and the Volts/Div is 20mV. Press the Trigger Menu button and set the trigger Type to Edge, the Source to CH1, the Slope to Rising, the Mode to Normal, the Coupling to HF Reject, and the level to about 15mV. These trigger settings will cause the oscilloscope to only capture a trace when there is a change in the coil voltage. You may need to adjust the trigger level to get it to capture a trace. Set the Sec./Div to 25ms.
- 3) Hold the magnet about 10-20 cm above the coil with the north pole facing down as shown in Figure 2. Drop the magnet through the coil catching it with a your hand or a piece of foam rubber. Hopefully the oscilloscope triggered and you have captured a trace. If it looks like the lower curve in Figure 1 press the RUN/STOP button to save it. If it didn't capture a trace you need to adjust the trigger level. Play with the level until you get a trace. (Also make sure the oscilloscope is in RUN not Stop mode!) You also may need to adjust the Volts/Div and Sec./Div

EXPERIMENT 10

until you have saved a good looking signal. Make a sketch of this waveform and label it "North Down" for your report.

4) Now reverse the direction of the magnet so that the North pole is at the top, but don't change the orientation of the coil. Press the RUN/STOP button to arm the oscilloscope and drop the magnet through the coil. When you get a good waveform save it and make another sketch labeling it "North Up" for your report.

QUESTION 2 - What is the difference between your two sketches? Explain this difference in terms of the change in flux. Are the waveforms consistent with the change in flux shown in Figure 1?

5) Arm the oscilloscope to capture a new waveform. Push the North end of the magnet into the same end of the coil as you did in 1) and rapidly pull it back out. Adjust the Volts/Div and Sec./Div until you get a waveform similar to what you had in 1). Make a sketch of this waveform and label it "Magnet In/Out".

The Current Induced By A Moving Permanent Magnet

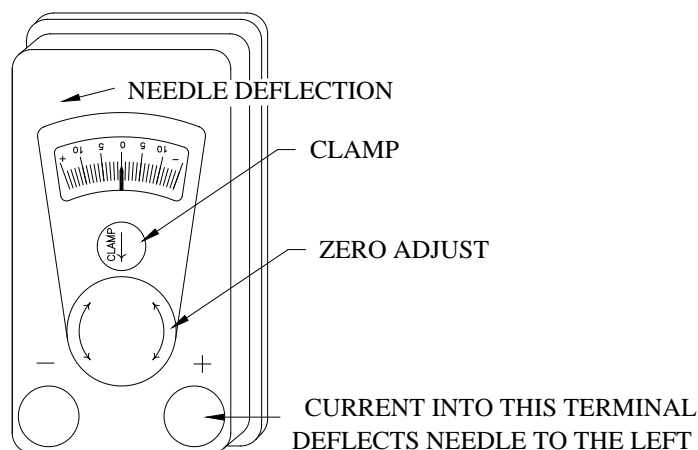


Figure 3 Diagram of the galvanometer used in today's experiment.

Figure 3 is a drawing of the galvanometer you will use in today's lab. Galvanometers are delicate and expensive, so please handle them carefully. The galvanometer is a very sensitive ammeter. One division on the scale is approximately one microampere, $1\mu\text{A}$. Before you move a galvanometer, you must CLAMP the needle movement by pushing the clamp button in the direction of the arrow shown on the meter. Conversely, before you can use the galvanometer to measure current, you must UNCLAMP the meter movement by pushing the button in the other direction. For the meter's safety, PLEASE CLAMP the meter movement when you are not using it. The "Zero Adjust" knob is used to set the needle to zero when the meter movement is unclamped and no current is flowing through the galvanometer. As shown in Figure 4, the galvanometers are built so that the needle deflects to the left when current is flowing into the right terminal. Full-scale deflection for these meters is about 10mA and the internal resistance is a fraction of an Ohm. You should take this into account before connecting the galvanometer to any voltage source other than that outlined in this procedure.

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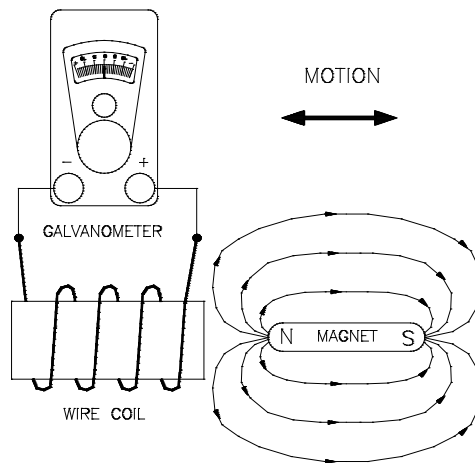


Figure 4 Diagram showing apparatus necessary to observe current induced by a moving permanent magnet.

6) Assemble the circuit shown in Figure 4 using the 20-turn coil. Unclamp the meter movement and zero the meter if necessary. Take the magnet and push one end of it into the center of the coil and watch the direction the needle on the galvanometer moves. Leave the magnet sitting in the coil and watch the needle go to zero. Now pull the magnet out of the coil and notice that the needle deflects the other way. You need only to observe these phenomena; no sketches are necessary.

7) Quickly push the north pole of the magnet into the coil and observe the direction the galvanometer needle deflects. The moving north pole of the magnet provides a CHANGING applied field toward the coil. Before you push the magnet into the coil, there is no magnetic field and therefore no flux. Once the magnet is in the coil there is a magnetic field approximately parallel to the area vector of the coil. This means there is a large flux.

QUESTION 3 - Is the direction of the field from the magnet pointing into the coil or out of it? What, therefore, is the direction of change in the applied magnetic field?

Now, from the direction of the deflection of the galvanometer's needle, find the direction of the induced current in your circuit. Look closely at your coil. From the direction of current flow determined by the galvanometer, determine which way the current circulates around the coil. Knowing the direction of the circulation, use the right hand rule to determine the direction of the induced magnetic field.

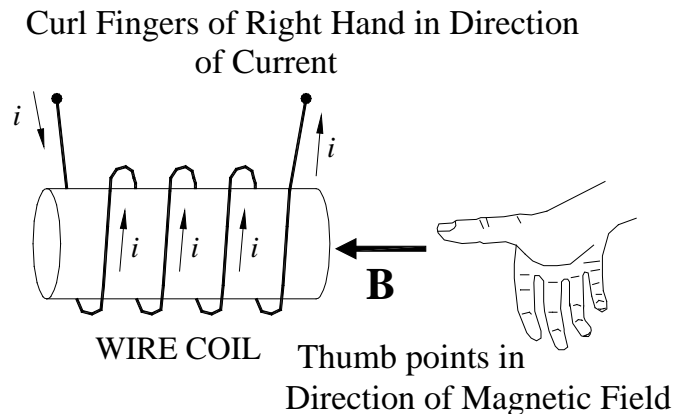


Figure 5 Diagram showing how to use the Right Hand Rule to determine the direction of the magnetic field in a coil with a current.

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To find the direction of the magnetic field associated with a current flow in a coil, the fingers of the **RIGHT** hand are curled around the coil with the fingers pointing in the direction of the current flow. The thumb (of the right hand) then points in the direction of the magnetic field. See Figure 5.

QUESTION 4 - Verify that the direction of the induced field is opposite the changing applied field. A written explanation should be included in your report along with a sketch showing the motion of the magnet, the polarity of the magnet, the direction of the **CHANGE** in the applied field, the direction of the induced current, and the direction of the induced magnetic field.

8) Start with the north pole of the magnet resting in the coil and quickly pull out the magnet. Record the direction of the induced current, and determine the direction of the induced magnetic field.

QUESTION 5 - Based on the motion of the magnet and the direction of the magnetic field from the magnet, what is the direction of the change in the applied field? Clearly explain your reasoning here. Does Lenz's Law appear to be obeyed?

QUESTION 6 - Explain the difference in behavior between step 3) where you push a north pole into the coil and step 4) where you pull a north pole out of the coil in terms of Equation 2. In other words, what does the motion of the magnet have to do with the sign of the change in the flux? Include a detailed explanation and sketch as part of your answer.

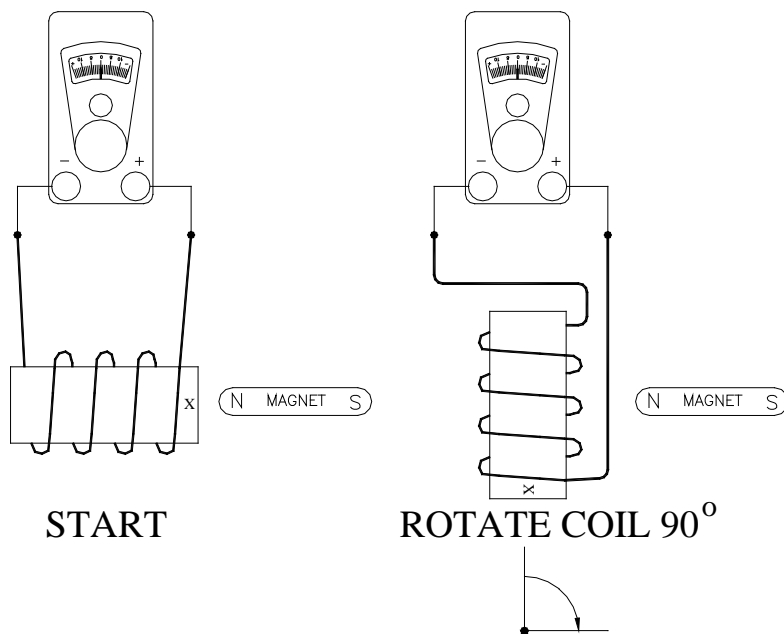


Figure 6 Diagram showing how to rotate coil 90 degrees relative to its axis.

9) Hold the north pole of your magnet close to the coil. Quickly rotate the coil 90° relative to its long axis as shown in Figure 6. If you do this right, you will observe a small deflection of the galvanometer needle. Record the direction the needle deflects on the galvanometer. From the current direction in the coil determine the direction of the induced field. Relative to the end of the coil originally near the magnet, is the direction of the induced field into or out of the coil? Is the direction of the change in the applied field along the axis of the coil, into or out of the coil?

QUESTION 7 - Explain this behavior in terms of the change in flux through the coil and Lenz's Law. Hint: This situation is either like pushing a north pole into the coil or like pulling a north pole out of the coil.

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Induced Current Is Proportional To The Rate Of Change Of Flux.

10) Assembled the circuit shown in Figure 4 using the 10-turn coil. Move the north pole of the magnet IN and OUT of the coil SLOWLY. Note the magnitude of the galvanometer deflection. Now move the north pole of the magnet in as fast as you can. Let the needle return to zero. Then pull out the magnet as fast as you can. (The pause allows the needle on the meter to relax to zero.) Note the magnitude of the deflection.

QUESTION 8 - Is this qualitatively consistent with Faraday's Law? Explain your answer.

11) Replace the 10-turn coil with the 2-turn coil in your circuit. Again push one end of the magnet into the coil as fast as you can. Record the magnitude of the meter deflection. Pull the magnet back out and again record the deflection.

12) Repeat the above experiment with the 20-turn coil. Record your results in a table.

QUESTION 9 - Do the magnitudes of the currents produced seem to be proportional to the number of turns in the coil as Faraday's law predicts?

A Change In Current In One Coil Induces A Current In Another Coil.

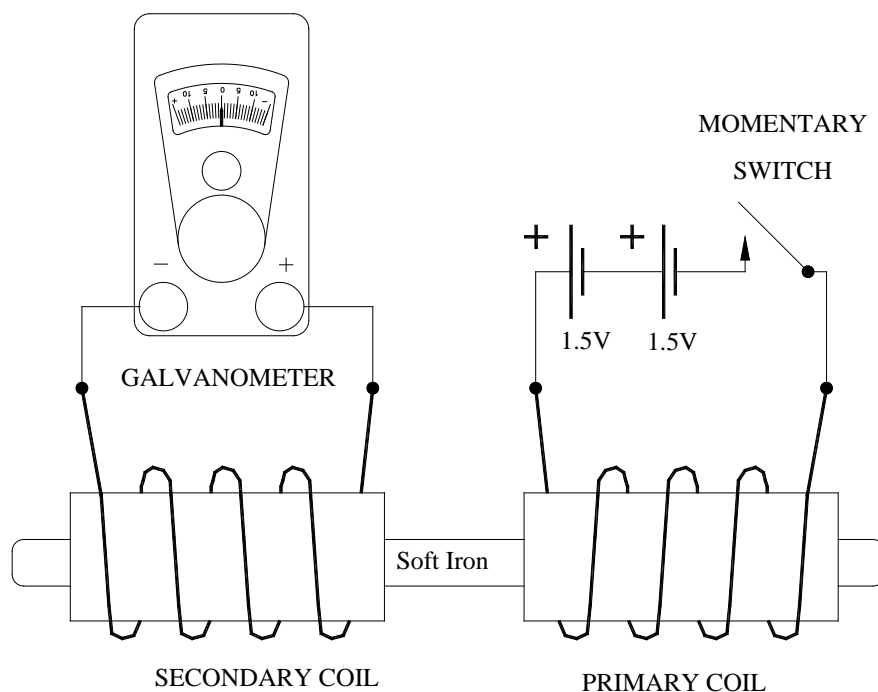


Figure 7 Schematic of the circuit used to investigate currents induced by a changing current.

13) Assemble the circuit shown in Figure 7. Use the 20-turn coil for the secondary and the many-turn coil for the primary. Look at the direction of the windings in your coils; assemble your circuit exactly as shown in Figure 7. DO NOT CLOSE THE SWITCH YET! The primary coil is the coil connected to the switch and the battery. The secondary coil is the one connected to the galvanometer. By opening and closing the switch, you will create a changing current in the primary coil. This change in current produces a changing applied magnetic field. The changing applied field induces a current in the secondary coil. The direction of the magnetic field from the induced current should be observed to oppose the CHANGE in direction of the applied field. Make sure the soft iron core runs through the centers of each coil.

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14) Close the switch and watch the needle on the galvanometer deflect until it stops. Now open the switch and the galvanometer should deflect the other way. Record the direction of the needle deflection when you close the switch and when you open it. Determine the directions that the currents circulate in both of your coils in both cases.

QUESTION 10 - Verify Lenz's Law by comparing the direction of the change in the applied field caused by closing the switch and the direction of the induced field from the current flow in the secondary coil. Do this same analysis for what happens when you open the switch. Be sure to include sketches for each case.

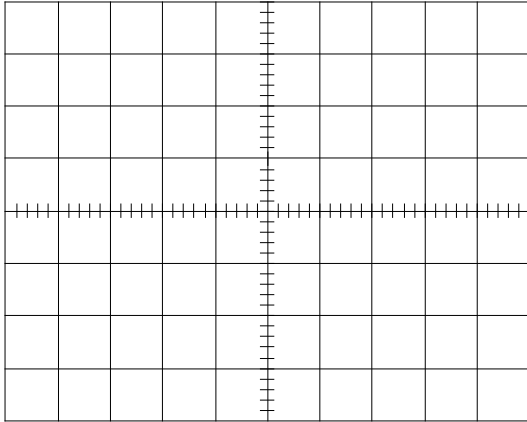
15) Remove the iron core and repeat the experiment, noting the magnitude of the deflection.

QUESTION 11 - From your observation, what must you conclude about the effect the iron core has on the flux that goes through the secondary coil?

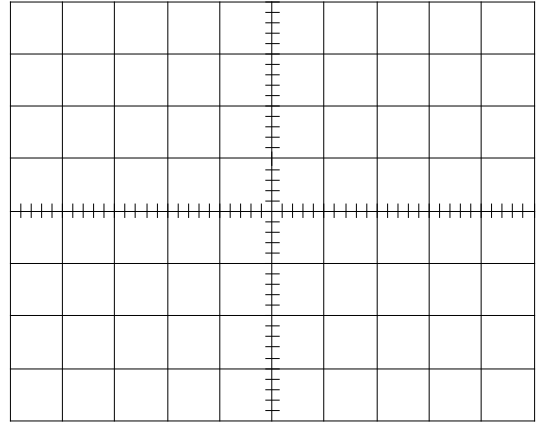
EXPERIMENT 10

Oscilloscope Scales For Waveform Sketches

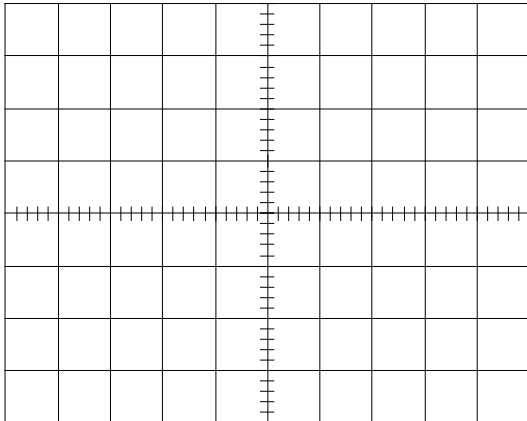
Sketch of _____
Volts/Div _____ Sec./Div. _____



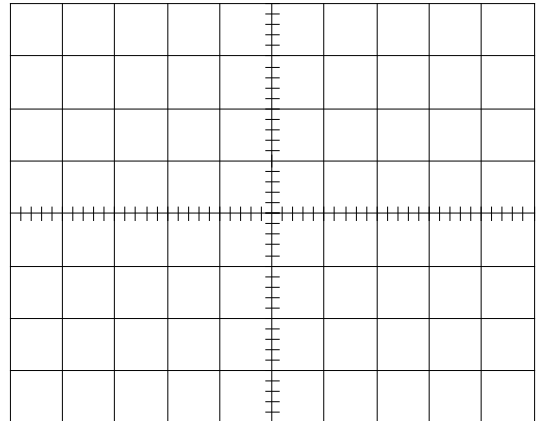
Sketch of _____
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EXPERIMENT 10

Experiment 11 - Build A DC Motor

An electric motor is essentially an electric generator operated in reverse. While a generator transforms mechanical energy into electrical energy, an electric motor transforms electric energy into mechanical energy. Your goals are to build a motor that spins fast and to be able to explain why the coil spins.

Apparatus

Small wooden blocks, permanent magnets, 12 Ga. copper wire, 22 or 24 Ga. varnished magnet wire, 5/64" drill bit, needle nose pliers with wire cutter, wire stripper, contact cement, and optional 5 minute epoxy.

Generating AC Voltage

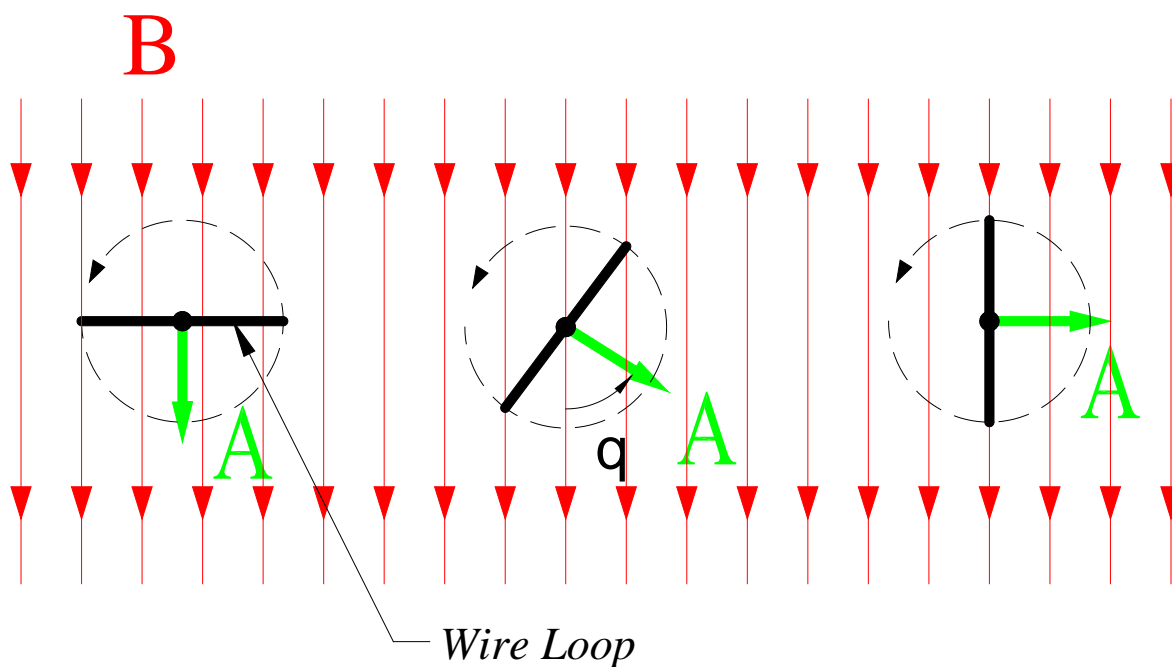


Figure 1 View looking along the axis of a rotating wire loop, viewed in three positions.

Imagine a rectangular loop of wire that is rotating in a uniform magnetic field. Figure 1 shows the position of such a loop at three different times. The magnetic field is drawn as a set of equally spaced down-pointing arrows. The left view shows a time when the wire in the loop is perpendicular to the magnetic field. This means the normal to the surface formed by the loop is parallel to the magnetic field so the flux in the loop is a maximum. In the middle figure, the wire loop is shown rotated by an arbitrary angle q from its position at maximum flux so the flux is $\Phi = AB \cos q$. Finally in the right figure, the wire is parallel to the field, which makes the normal perpendicular to the field and therefore the flux is equal to zero.

As the loop changes from one position to the other, the flux through the loop changes. As we learned in a previous lab, this **change** in the flux leads to an induced voltage in the loop of wire. A coil rotating in a uniform magnetic field is the basic principle behind the practical use of

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electrical power and it naturally produces the sinusoidally alternating current that we depend on everyday.

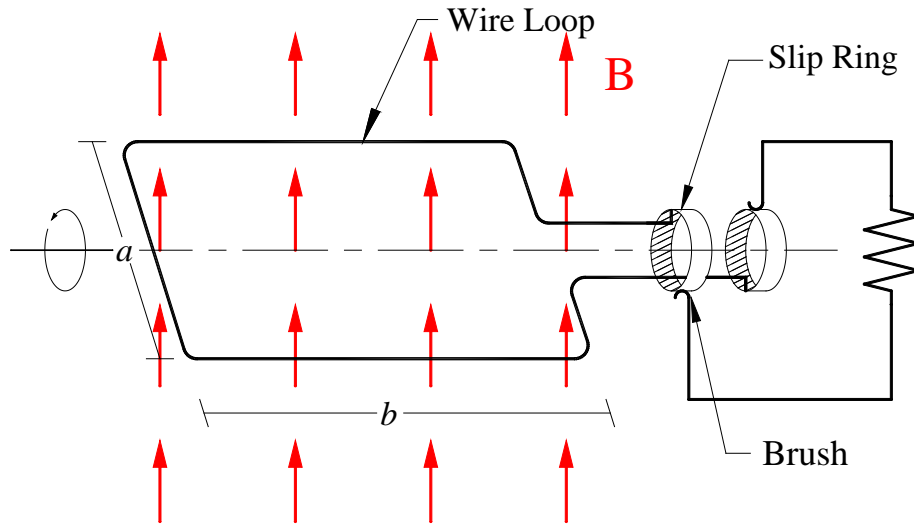


Figure 2 A wire loop spinning in a magnetic field makes a simple ac generator.

Figure 2 shows the configuration of a simple generator of ac power, which is sometimes called an *alternator*. Imagine a region of uniform and steady B field, so that all field lines are parallel and equally spaced. Place within that field a rectangular loop of wire with dimensions a by b and mounted on a shaft that can rotate about an axis perpendicular to the magnetic field. You can see from the diagram and the previous discussion that the flux for any general value of the angle q is:

$$\phi = Bab \cos q.$$

If the loop rotates uniformly in time on its axis as shown, the angle q increases proportionally with time

$$q = 2\pi f t$$

where $2\pi f$ is the angular frequency in radians per second and f is the revolutions per second, the *frequency*. Combining the above two equations yields the flux as a function of time

$$\phi = Bab \cos(2\pi f t).$$

Taking the derivative of this gives us the change in flux with time, which equals (except for a minus sign) the voltage induced in a single loop of wire

$$\frac{d\phi}{dt} = - Bab 2\pi f \sin(2\pi f t).$$

If N turns of wire are closely wound on the same frame, and letting $V_0 = BabN2\pi f$, then the total induced voltage in the wire is

$$V = V_0 \sin(2\pi f t).$$

The above describes a very basic ac generator. Both the voltage across and the current through a constant load resistor vary sinusoidally with time. Thus, we see that the sinusoidal time variation of ac electrical power is the natural result of rotating coils inside a magnetic field. So

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the standard sine wave form that we learned about earlier is not an arbitrary "classroom example", rather, it is a fundamental consequence of how electrical generators produce power.

If the wire loop in the generator rotates sixty times per second, or 3600rpm, the variation in voltage goes through sixty full cycles per second; that is a frequency of 60Hz. In support of every wall outlet are big spinning generators a lot like the above simple model, although full of iron, water-cooled copper wire, and more elaborately engineered. Usually an electromagnet supplies the magnetic field and it is made to spin on the shaft, while the coils for the power output are stationary. This makes it much easier to send out the high voltages and currents produced by a 1000 Megawatt power-plant generator. If you think about it, the fact that it does not matter whether the coil spins or the magnet spins implies that it is only the relative motion that counts in figuring the flux changes.

Work is required to accomplish the moving of the coils through the magnetic field that produces the ac power. This work is required in order to overcome the forces created by the current-carrying conductors moving within a strong magnetic field. Overcoming these magnetic forces can require tremendous torques from the driving machinery. Thus we can properly think of a generator as converting this mechanical work into electrical energy. Steam turbines, gas turbines, or large internal combustion engines supply the mechanical power. Large generating plants generally use high-pressure steam heated by a nuclear reactor, burning gas, coal, or oil. The College uses three natural gas fueled internal combustion engines to generate up to 3 megawatts of electrical power.

Typical values for such a generator could be $B=0.5\text{tesla}$, $ab=0.5\text{m}^2$, $N=100$, and $V_0=35,000$ volts. A current of 29 amps would produce one megawatt, which is about the size of the College's generators. Such a generator weighs many tons. A modern commercial power-plant generator usually develops kiloamperes of current at voltages two or three times higher which deliver several hundred megawatts of ac power. The third generator house at Grand Coulee Dam in Washington State has seven 750 megawatts generators installed! Approximately 2000 of these large megawatt generators are installed within the entire American utility network.

AC Motors

Synchronous Motors

The electrical generator described above can be "run in reverse" to act as a motor. If alternating electrical current is applied to the wire, then the coil of wire will spin in the magnetic field. Thus, whereas a generator converts mechanical energy needed to rotate the coils into electrical energy that is sent along the wires, a motor receives electrical energy through the wires and converts it into (rotational) mechanical energy.

Of course, something needs to provide the alternating current to run the motor and this is typically done by having a generator as well (e.g. when you plug in your fan, the power going into it is produced at the local power plant, this alternating current then causes a coil of wire to spin in a magnetic field and run your fan). To picture this process, think of two identical single-loops as described above, the two built exactly the same, but with the ac current output of one supplying an ac current input to the other. The conductor loop that receives current feels magnetic torque from the steady magnetic field around it. As long as the two identical machines move in step, with the same current and speed, the motor can supply the same amount of mechanical power that the generator is being driven with (apart from some small losses). Recall that when you wind a crank to lift a weight steadily on a cord, the work you exert per time is nearly the same as that you would use to raise the weight directly at the same speed. So the

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identical generator and motor move at the same speed, with the current and torques being almost equal. The generator takes in mechanical power and the motor supplies it. Such a motor is said to be *synchronous* because it spins at the same frequency as the generator. The motors in electro-mechanical clocks are synchronous motors. The ac generating plants make it a point to put out exactly the correct number of ac cycles per day to keep Americas clocks running on time.

DC Motors

A uniformly rotating loop in a steady magnetic field naturally generates ac power; likewise, ac motors spin when provided with an ac current or a rotating field made by alternating current. However, if we would like to run our motor from a dc power source such as a battery(as we will do in lab today), we will need to slightly modify our motor's design. How can this be accomplished?

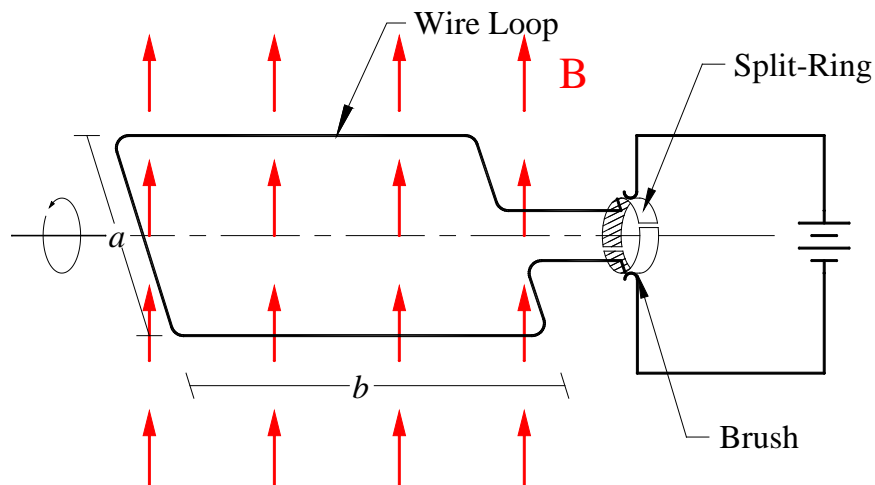


Figure 3 Diagram of a dc commutator motor.

Think about what would happen to the motor shown in Figure 2 if it were connected to a battery. Current would flow in the wire loop creating a magnetic field. This field would then align itself with the uniform magnetic field it is sitting in. The motor would wobble a bit, then just sit there aligned with the B field.

The key to making a motor run off of dc current is switching. If the current leads on the simple alternator described earlier are reversed every half-turn of the wire loop there will be an induced voltage which gives rise to a torque. A *commutator* is a clever mechanical device that automatically manages this. A split-ring is mounted on the shaft of the wire loop, with sliding contacts that are able to carry current even when the shaft is turning. The purpose of the split-ring is that every half turn, the wire that is connected to the positive side of the battery is switched. So the direction of current around the loop is switched every half turn. Thus the magnetic field in the loop is anti-aligned with the constant magnetic field. The loop "wants" to constantly align itself with the magnetic field so it spins in an attempt to maintain this alignment, but just about as the loop becomes aligned with the B field the switch changes the direction of current.

Real commutators have several segments, on which the contacts slide as the shaft turns. The sliding contacts are known as *brushes*. Sometimes the contacts are literally wire brushes, but more often they are spring loaded graphite blocks. A brush on a large dc motor that runs a ski lift

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maybe 4x6cm in cross-sectional area and carry several hundred amps of current. A motor like this might have a dozen pairs of loops with many turns per loop wound on the rotor.

DC Brushless Motors

One problem with the above motor scheme is that the switching contacts spark and wear as the full current of the coils turn on and off. You may recall that current flowing in an inductor acts just like the inertia in a mechanical flywheel and that the voltage produced is:

$$V = -L \frac{di}{dt}.$$

where L is the inductance in the coils and di/dt is the rate of change in the current. So the faster a motor shaft turns, the faster the rate of switching must be, which causes a large voltage to be produced as the switch turns on and off. This makes the switching contact wear out much faster. A popular scheme around this involves using a small digital computer and solid state switches to make a *dc brushless* motor. This type of motor is very similar to the ac induction motor in that the central rotor uses a set of permanent magnets for the magnetic field and the coils around the rotor are switched on and off to create a rotating magnetic field which pushes the rotor around. The computer calls for a small signal that senses where the spinning rotor is in relation to the driving coils and turns on and off the current in the coils. Since there are no mechanical contacts these motors are electrically quiet and have no contacts to wear out. A motor as small as 2cm in diameter by 4cm long may draw 25 amps at 10V which corresponds to approximately 1/3 of a horsepower!

Build a dc Motor

1) Study the Assembly Plan of the Johnson DC Motor. The motor consists of a **Wooden Base** into which you will drill 8 holes. Two short pieces of heavy insulated wire bent as shown on the plans are pressed into four of these holes to form a **Battery Holder**. Two longer pieces of heavy un-insulated wire are bent to form the **bearing** point for the coil **axle** and to make electrical contact with the battery. These wires are labeled **Motor Support** on the plans. A motor **Coil Winding** is made by forming small gauge magnet wire into several loops with the protruding ends of the wire forming the axle of the motor. (Note that wire diameter is inversely proportional to the gauge size, so a 24 gauge wire is smaller than a 12 gauge wire.) The wires from the coil rest in two V-bends made in the Motor Support, which form the bearing point for the motor's axle. A small disk magnet is glued to the block under the coil to make the stationary magnetic field **B**. Insulation is scrapped entirely off one end of axle and selectively scrapped of the other end to form the commutating switch. The partially scrapped-off-end forms half of a split-ring. So this motor only draws current over half of its rotation. The V-notches in the Motor Support wires act as the brushes.

2) Take the copy of the Johnson DC Motor plan and lay it over a 6 x 10cm block of wood. Notice the black dots showing the location of the eight holes that need to be drilled. Mark the locations of the (8) 5/64" diameter holes and drill the holes approximately halfway into the wood. Try not to wiggle the drill from side-to-side as you drill the holes as this will make the diameter of the holes too big. The 12 Ga. copper wire needs to fit tightly into these holes (this is called a "press fit"). Cut two lengths of bare 12 Ga. copper wire for the Motor Support as shown on the plans. These two wires will provide the current path from the battery to the motor coils and double as the pivot points for the motor. Bend the wire as shown on the plans using a needle nose pliers. Make the bends in the wire starting from one end and working to the other. Mark where the bend should be with a pencil or felt tip pen, then hold the wire with the pliers about

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1/16" from where you want the bend to be. Sharply bend the wire down to the angle you want. To make the "V", first make a 45° bend down, then holding with the tip of the pliers at the bend point, bend up 90°, hold with the tip of the pliers at the bend point, and bend down 45°. This should give you a nicely formed bearing point for the motor axle to run in. If you have sharp notches in the wire in the bearing groove, you can use a small piece of sandpaper or crocus-cloth to polish away the rough marks. When you are happy with the shape, press the Motor Supports into the holes in the wood block. They should be a nice tight fit. Cut two lengths of 12 Ga insulated copper wire for the Battery Holder. Strip the insulation from the ends of the wires as shown on the plans and bend to the shape shown. These wires are pressed into the wood block and help locate the C-cell battery so that it can make good electrical contact with the Motor Support wires. Now bend and adjust the Motor Support wires and the Battery Holder wires so that the battery "snaps" in place when you push it between the Support Wires (this may take some trial and error). Once you are satisfied with the fit, remove the battery from the "holder". Glue the magnet to the wood block by spreading a thin layer of contact cement on the wooden block and a thin layer on the magnet. Let the cement dry until it is no longer "tacky-to-the-touch". Position the magnet carefully over the cement on the block because it will bond to the wood instantly upon contact. Press the magnet into place.

3) Make the motor *Coil Winding* by winding circular coils of wire about 2 cm in diameter. (You could alternately make rectangular coils as shown on the plans.) Use anything you can find as a form (a dry marker, a glass sample vial, or whatever.) Use 24 to 22 gauge magnet wire. The magnet wire is coated with an insulating varnish that will be scraped off to make the switching "brushes". The more turns, the more force you will get, but if the coil is too heavy it will sag on its wire axles. Also the heavier gauge wire (smaller gauge number) will make a stronger rotor mechanically, but will draw more current, which will make the battery run down faster.

Bring the leads of the coil out along the center of the sides of the coil along the axis it will rotate on. See Figure 4 for a detailed drawing of how to wrap the wire around the coils and out through the middle to form the axles. If your coil is made from 24 Ga wire you might need to apply a small amount of 5 minute epoxy to the wires to stiffen the coils so that it stays in shape as you try to adjust the balance. Do this under a fume hood and use exam gloves when working with the epoxy. Allow the epoxy to cure and remove the coil from your form.

4) Make the switching brush contacts by scraping off the insulation all the way around one end of the wire axle of the motor coil to make electrical contact continuously as the coil turns. See the motor plans. On the other axle end, scrape off about half of the insulation to act as a switch so that when the current turns on the field from the coil is anti-aligned with the stationary **B** field and turns off just before the coils field aligns with the stationary field. See the detail on the plans. The motor "brushes" are made of a single piece of wire coming in contact with copper support wires. The switch is made by the absence or presence of the varnish on one axle end. The varnish is very tenacious, so inspect the wire carefully to see that you get it all off to make good electrical contact. A magnifying glass or stereo microscope can help to see varnish that hasn't been fully scraped off.

5) With the battery removed from the holder, place the coil into the V-notches on the motor support. Straighten and adjust the leads of the wires coming out the sides of the coil so that the coils spins freely and does not have any "low" spots. Adjust the height of the V-notches in the support wires so that both ends of the coil are at the same height above the block. Install the battery in the holder and give the coil a little push to get it moving. If you were careful in your construction you should have a working motor. Once your motor spins, try optimizing the rate of spin by making small bends in the coils or wire axles. This motor will work best if the magnetic

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force produced on the coils pulls it down instead of forcing it up off the V-notches. Try reversing the coil to see which way your motor works better.

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Trouble shooting

If your motor doesn't work the first time try the following suggestions:

Is the battery making good electrical contact with the coil?

Hold on to the coil as you spin it around, if the battery is making contact you will feel a force on the coil and possibly see a small spark on the copper V-contacts.

If you don't get a spark or force look closely at the 12 Ga. copper wires making contact with the battery.

You might have to bend the Motor Support wires slightly to make good contact with the battery.

Remove the coil from the Motor Supports and carefully exam regions with the scrapped-off-insulation. Make sure it is scraped clear to the wire.

If you have good contact but the motor still does not run, make sure the coil can spin freely in the V-notches. Is it hitting the battery or magnet? You might have to bend or adjust the Motor Supports or make the coil slightly elliptical so that the coil spins freely without hitting anything. Alternatively, the coil might not be balanced. If the coil wants to rotate strongly to one equilibrium position (in the absence of the battery), the torque from the magnetic field might not be strong enough to spin the coil. You can wrap a few turns of wire around the light side to balance the coil or you may bend it slightly. Finally, if you scraped the insulation off the switch end incorrectly you might have made a motor that only wants to align itself with the magnetic field, not spin around continuously.

Question/Discussion

Using pictures and/or diagrams, show and explain how your motor works.

References

Haliday, Resnick, and Walker, *Fundamentals of Physics 7th Ed*, Sections 28-8 to 28-9 and 29-6 (Pages 750-754, 778-779)

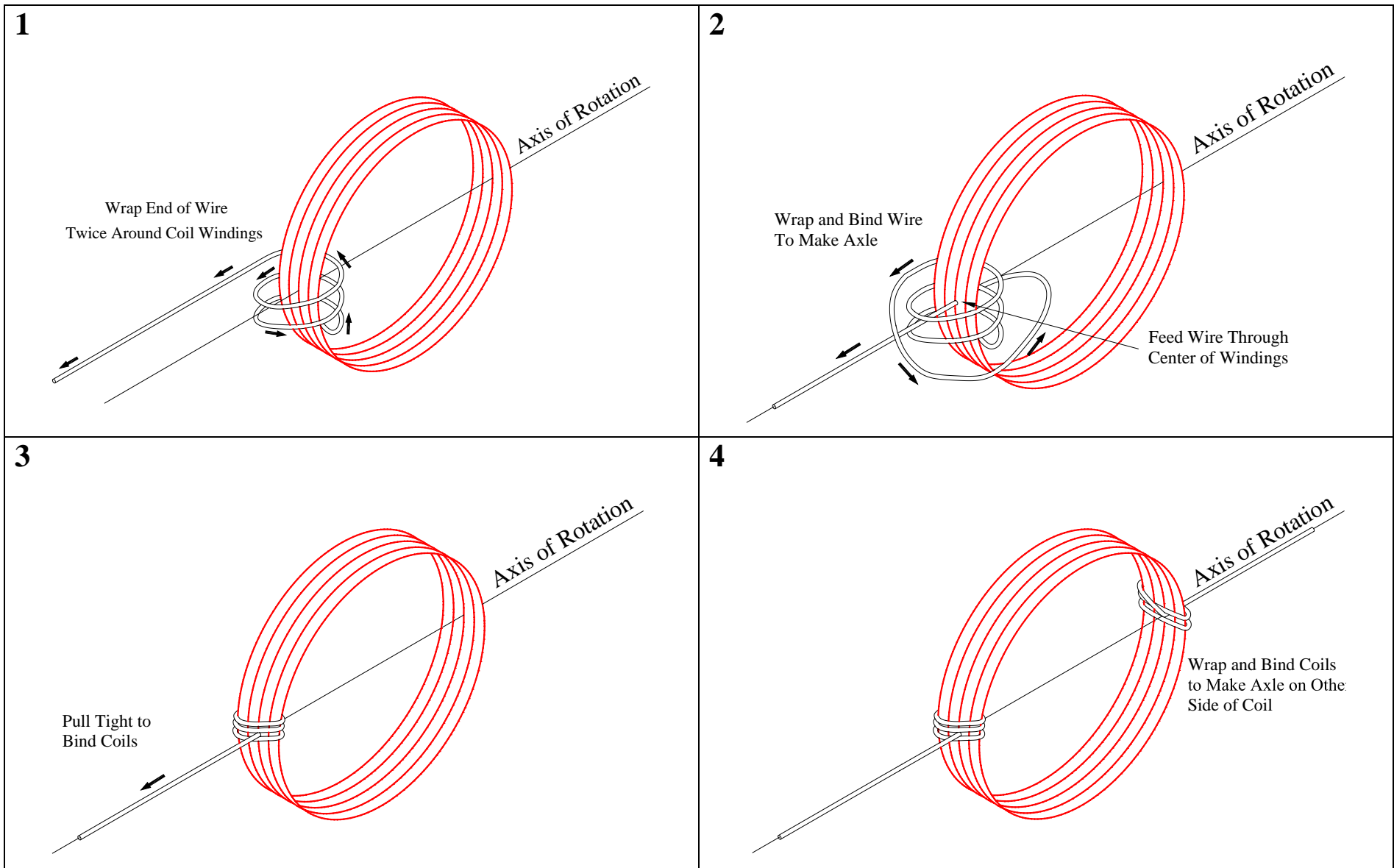


Figure 4 Drawing showing how to wrap wire ends to make axles on Motor Coil Windings.

Assembly Plan of Johnson DC Motor

