

**Physics 213**

***University Physics III***  
***(Electromagnetism)***

**Lab Manual**

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## Physics 213 Lab Report Guidelines

Students are required to read the lab manual, and collect their questions before coming to the lab. Each student should have a notebook for the lab. Please bring with you some common stationery to the lab, including a pen, a calculator, a flash drive, and a camera.

Laboratory report for each lab is due in one week following the date of the completion of the experiment, unless otherwise arranged. No absences from the labs or late lab reports can be accepted, except for pre-approved and extenuating circumstances.

All text portions of the lab reports should be prepared using Microsoft Word or a compatible word processor. All graphs in the lab reports should be prepared using Microsoft Excel or a compatible graphing program. Hand-drawing diagrams may be attached to the lab report. If you use a photo, please crop the photo so that only necessary information is shown. You should submit a printed hardcopy for the lab report. A sample student lab report will be posted online.

All lab reports should have the following organizational structure:

- 1) Title page — Title of the lab experiment, date of the lab experiment, your name, group members' names, course number, and instructor for that lab.
- 2) Introduction — Explain the purpose of the experiment. Make a brief statement of what the experiment is about. Explain possible applications of the physics you learn in that lab.
- 3) Background principles — Include and explain any relevant background physics concepts and/or mathematical equations used in data collection and experimental analysis. Include here any derivations asked for in the manual which are necessary for analyzing the data.
- 4) Experimental procedures — Include a complete description of the instrumentation used, the manner in which you used it, and the quantities to be measured. Sketch the equipment detail and the experimental setup. You may also include cropped photos. The sketches and photos should be supplemented with legible notes. Identify the strengths and weaknesses of the experimental setup, including any special cautions observed. Describe the chronological procedure of how you conduct the experiment, including demos performed by the instructor, problems encountered in the course of the lab, and how you overcame them.
- 5) Results and discussion — Present your experimental findings, along with relevant data tables, data printouts, graphs, spectra, or images obtained. Describe how you analyze and interpret your data in light of the theory developed in part 3 to reach your final results. Answer questions that are raised in the lab manual.
- 6) Conclusions — Summarize the major findings and accomplishments of your experiment. Explain any errors incurred or discrepancies with theory, and identify where further work may be applicable.

# PHYS 213 Lab 1: Mathematica Tutorials

*Mathematica in Physics*

## Creating, Solving and Plotting Physics Equations in Mathematica

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### Mathematical Operations

*Mathematica* is a wonderful tool for doing mathematics, solving equations, and plotting functions, especially as they relate to Physics. This is a short tutorial to help introduce to you some of the functionality of this awesome tool. There are many things which you will do with *Mathematica* which you can do with other tools such as your programmable calculator. But, trust me, *Mathematica* blows your calculator out of the water! For now, we'll start slow, to get you started and not overwhelmed.

When you open *Mathematica* on your computer, you'll find a menu up top, a blank "notebook" to the left, and a "palette" -- Basic Math Assistant -- to your right. If the palette is not there, go to "Palettes" in the menu, and choose Basic Math Assistant.

The menu is for accessing files, controlling format, choosing palettes and style, and controlling evaluation. We won't have to use that much for this exercise.

The palettes are for inserting numbers, symbols, formatting expressions and inserting functions and commands into the notebook.

The notebook is where the majority of your work will be done. It is made up of "cells", into which just about anything can be typed, depending on the cell format. However, the primary purpose of the cells is for entering mathematical expressions for the sake of evaluating them, defining them, plotting them, or whatever else you might do to them.

For example, you might enter a simple addition formula:

$$8 + 12 - \pi$$

I have entered this formula as text, so *Mathematica* just reads this as a line of symbols. In the notebook you have opened, everything you type is in Input format, which is the format you want for evaluating mathematical expressions. When I type the above expression in the Input format, I have to type "Shift+Enter", and so get:

```
In[1]:= 8 + 12 +  $\pi$ 
```

```
Out[1]= 20 +  $\pi$ 
```

If you do want to type text as I am doing here in order to make comments, pressing "Alt+7" converts the cell you are in to "text" format. Notice that a "cell" consists of an input line, and an output line.

Notice that the output to the input expression is a whole number added to Pi. That is because the most precise way to express the irrational number Pi is to use the symbol. To explore this issue further, first, you need to know that *Mathematica* stores the data from cell 1 for as long as it is open, unless you tell it to erase it. You can access it by typing the percent (%) key, followed by the cell number (1):

```
In[2]:= %1
```

```
Out[2]= 20 +  $\pi$ 
```

To get a rational number of a certain precision, you can type `N[%1,30]`, where the N is the command to convert an expression into a number, and the 30 is telling the computer that I want 30 digits of precision:

```
In[3]:= N[%1, 30]
```

```
Out[3]= 23.1415926535897932384626433833
```

*Mathematica* can go as precise as you wish. However, *Mathematica* is touchy about precision. For example, if we had used a decimal in the original expression, say 12. instead of 12, *Mathematica* automatically limits the precision to just six figures. It's not *exactly* significant figures, but something like it. Let's make that switch and see how *Mathematica* handles it.

```
In[4]:= 8 + 12. +  $\pi$ 
```

```
Out[4]= 23.1416
```

```
In[5]:= N[%4, 30]
```

```
Out[5]= 23.1416
```

All the precision of Pi is lost, because *Mathematica* has assumed that the 12. is an approximation, and therefore keeping Pi infinitely precise is misleading.

The important lesson here is that *Mathematica* treats decimals as approximate numbers of limited precision, while it treats integers and irrational numbers as exact. This can make a difference when solving the equations you are working with.

Ok, other things to notice. Addition looks normal. So does subtraction ("-"), multiplication (\*, or just space) and division (/).

But to specify the precision we needed to invoke a Function, or really, a Command, N. Like ALL commands/functions in *Mathematica*, it has a name ('header'), N, and an argument (enclosed by square brackets) with one or more "slots" for input, separated by commas.

The name of the built-in function ALWAYS begins with a capital letter.

The first slot is usually the input for the function, in this case the output from cells 1 or 4. The second slot is an option that specifies the precision of the output of the function. Each "built-in" command/function has its own set of slots according to its definition. The available functions can be found by going to the Documentation Center through the Help tab of the menu.

Simple functions just have the single slot for the input, as in:

```
In[6]:= Cos[%1]
```

```
Out[6]= -Cos[20]
```

Notice that *Mathematica* does not convert to decimal form unless it \*has\* to. The best answer to the question, "what is the cosine of 20 + Pi radians" is "the negative cosine of 20". (Recall the trig addition formula, cosine(a+b) = cosine a cosine b - sine a sine b, and that cosine Pi = -1.) To make *Mathematica* reduce the accuracy of the answer and give you a decimal, you need to use the command, N. Or, you could introduce decimal precision in any of the inputs of the problem. Consider:

```
In[7]:= N[%6]
```

```
Out[7]= -0.408082
```

```
In[8]:= Cos[ $\pi$  + 20.]
```

```
Out[8]= -0.408082
```

Still another way to do it is to use the Post Fix notation //N.

```
In[9]:= %6 // N
```

```
Out[9]= -0.408082
```

Finally, notice that in input line 8, square brackets are used to group the input into the cosine function. The square brackets [] are only used for grouping the inputs to a function/command. Regular parentheses () are used for grouping numbers or variables in algebraic operations, just as they are ordinarily used. A third, very important kind of delimiter, {}, or curly brackets, are used for collecting and inputting multiple expressions for functions, or simply for evaluation. Here are some examples:

```
In[10]:= {3 + 5, 92.2 + 322.1, Cos[2.55]}
```

```
Out[10]= {8, 414.3, -0.830054}
```

```
In[11]:= N[{ $\pi$ , e,  $\sqrt{2}$ ,  $\sqrt[3]{5}$ }, 10]
```

```
Out[11]= {3.141592654, 2.718281828, 1.414213562, 1.709975947}
```

Oh, and notice that the output in both cases is contained in curly brackets as well. If you want to recall just one of those values later on, you need to Pick it, like so

```
In[12]:= First[%11]
```

```
Out[12]= 3.141592654
```

or if you wish to obtain the second value from the list in output line 11, you can type

```
In[13]:= %11[[2]]
```

```
Out[13]= 2.718281828
```

## ■ Exercises

1. Calculate  $(520 - 330)/225$ ,  $990 * 23 - 3400$ , and  $12.4 * \text{Sin}[2.1]$ . Express your results in 6-digit precision.
2. Evaluate in six-digit precision the cosine, sine, tangent, the square, the cube, the natural log, and the natural exponent for two inputs: 1.23 and  $\pi$ .

## Expressions and Equations

Any symbol that has not already been used as a built-in command is fair game for being a variable in *Mathematica*. You need to be careful in naming variables and in using them in expressions. For example, if I make *fun* and *gun* to be variables, and I want to multiply them, I must write *fun gun* or *fun\*gun*, but not *fungun*. The last option creates a new variable, *fungun*.

The equal sign (=) assigns a value to the variable on the left. For example,

```
In[14]:= fun = 3.2
```

```
Out[14]= 3.2
```

```
In[15]:= fun
```

```
Out[15]= 3.2
```

This is useful for assigning value to constants, like  $g = 9.80$ , or  $c = 2.998 \cdot 10^8$ . *Mathematica* will remember that value for *fun* until you clear it or close the program.

```
In[16]:= Clear[fun]
```

```
In[17]:= fun
```

```
Out[17]= fun
```

You can also define a variable in terms of other variables.

```
In[18]:= gun = x + y
```

```
Out[18]= x + y
```

In effect, I have defined *gun* to be a function of the variables *x* and *y*. This is the simplest way to define functions of variables in *Mathematica*, but it is not necessarily the most useful.

Now, if *x* and *y* have fixed values, then that will fix the value of *gun*, as well.

```
In[19]:= {x = 4.3, y = 2.4}
```

```
Out[19]= {4.3, 2.4}
```

```
In[20]:= gun
```

```
Out[20]= 6.7
```

If I change the values of *x* and *y*, *gun* changes, too,

```
In[21]:= {x = 2.3, y = 1.4}
```

```
Out[21]= {2.3, 1.4}
```

```
In[22]:= gun
```

```
Out[22]= 3.7
```

If I want to work with the variable expression again, however, I need to clear the values of *x* and *y*. (For example, if I want to take the derivative of the function, or if I want to solve for some of the variables, as considered a bit further below.)

```
In[23]:= {x = ., y = .}
```

```
Out[23]= {Null, Null}
```

or

```
In[24]:= Clear[x, y]
```

```
In[25]:= gun
```

```
Out[25]:= x + y
```

Now, let's say that I know the function *gun* takes on a certain value, and I want to know what possible values the variable *x* can take. *Mathematica* has the command for you, called *Solve*! In the input below, I am asking *Mathematica* to tell me, if *gun* = 5.4, what are the possible values of *x*.

```
In[26]:= Solve[gun == 5.4, x]
```

```
Out[26]:= {{x -> 5.4 - y}}
```

The answer should be  $x = 5.4 - y$ , and that's what the output is saying, kind of. However there are several very important things to note here.

First of all, when I wanted to solve for *x* when *gun* = 5.4, I didn't set *gun* = 5.4. I wrote something different, *gun* == 5.4. The second equal sign changes the meaning from "permanent assignment" to "conditional assignment". The important thing about this is that by posing the question, "If *gun* = 5.4, what is *x*?" I don't overwrite the fact that *gun* = *x* + *y*, which I would have done if I used the single equals sign.

The second thing to note is the output. The arrow symbol is used instead of an equality. (One can type the arrow symbol in an input line by typing "-" and then ">".) Again, the equality would defeat the purpose of treating *x* as a variable, by assigning the value in this case to *x* permanently. The arrow is called a "rule". It completes the sentence, "If *gun* = 5.4, then  $x = 5.4 - y$ ." If I do wish to assign a variable or function that value from now on, I do the following:

```
In[27]:= temp[y_] = x /. First[%26]
```

```
Out[27]:= 5.4 - y
```

In this case, I've told *Mathematica* that the solution for *x* when *gun* = 5.4 is a function (called *temp*) of the variable *y*. The underscore after the *y* is necessary if I want to leave the names of the variables undetermined. Whatever value or variable is put into that first slot takes the place of "y" in the definition of the function "temp".

```
In[28]:= temp[y]
```

```
Out[28]:= 5.4 - y
```

The function works just as well if I call the variable "z" instead.

```
In[29]:= temp[z]
```

```
Out[29]:= 5.4 - z
```

Remember that `First[%]` extracts the expression from the brackets in the previous output. The symbol `/.` means, "evaluated at", and should always be followed by a rule indicating a temporary replacement of the variable in front of the `/.` symbol. The input line would read, "*temp* equals *x*, when *x* is evaluated according to the rule given in the first slot of the bracketed expression in the previous output." The use of the equals sign means the assignment to *temp* is permanent, while the variable *x* is left as an undetermined variable.

If I want to define a variable *temp* using a different possible value of *x* (say from a different solution involving *x*) then I could type this.

```
In[30]:= temp = x /. x -> 2.3
```

```
Out[30]:= 2.3
```

I have assigned a possible value of *x* to *temp*, without requiring *x* to take on that value permanently. The value was transferred to *temp* through *x*. The variable *x* remains undeclared.

```
In[31]:= x
```

```
Out[31]:= x
```

*Solve* works for any algebraic expression, even very nasty ones.

```
In[32]:= tun = x^3 - 5 x^2 + 3 x - 7
```

```
Out[32]:= -7 + 3 x - 5 x^2 + x^3
```

In[33]= **Solve**[**tun == 0, x**]

$$\text{Out[33]}= \left\{ \left\{ x \rightarrow \frac{1}{3} \left( 5 + \left( 152 - 24 \sqrt{33} \right)^{1/3} + 2 \left( 19 + 3 \sqrt{33} \right)^{1/3} \right) \right\}, \right. \\ \left. \left\{ x \rightarrow \frac{5}{3} - \frac{1}{6} \left( 1 + i \sqrt{3} \right) \left( 152 - 24 \sqrt{33} \right)^{1/3} - \frac{1}{3} \left( 1 - i \sqrt{3} \right) \left( 19 + 3 \sqrt{33} \right)^{1/3} \right\}, \right. \\ \left. \left\{ x \rightarrow \frac{5}{3} - \frac{1}{6} \left( 1 - i \sqrt{3} \right) \left( 152 - 24 \sqrt{33} \right)^{1/3} - \frac{1}{3} \left( 1 + i \sqrt{3} \right) \left( 19 + 3 \sqrt{33} \right)^{1/3} \right\} \right\}$$

Notice that there are three rules of replacement possible, corresponding to the three solutions that exist when solving for a third order polynomial. The first solution given is real, while the next two are complex numbers (complex conjugates). If I want the first expression for later use as a function in its own right, I would do this:

In[34]= **soln = x /. %[[1]]**

$$\text{Out[34]}= \frac{1}{3} \left( 5 + \left( 152 - 24 \sqrt{33} \right)^{1/3} + 2 \left( 19 + 3 \sqrt{33} \right)^{1/3} \right)$$

In[35]= **N[%]**

Out[35]= 4.67857

The variable x has still not been assigned a value.

In[36]= **x**

Out[36]= x

A solution doesn't have to involve numbers. It can be a representation of one variable in terms of other variables, obtained from an algebraic expression. For example, if  $3 a b + 5 b c = 7 c d - 4 d$ , and you would like to solve for  $d$  in terms of the other variables, you could type:

In[37]= **Solve**[**3 a b + 5 b c == 7 c d - 4 d, d**]

$$\text{Out[37]}= \left\{ \left\{ d \rightarrow \frac{3 a b + 5 b c}{-4 + 7 c} \right\} \right\}$$

If that solution is something worth keeping around, you could assign it to another, more descriptive name, as we did before:

In[38]= **dist = d /. %[[1]]**

$$\text{Out[38]}= \frac{3 a b + 5 b c}{-4 + 7 c}$$

And you could obtain numerical values for particular values of your input variables, a,b and c.

In[39]= **dist /. {a -> 2.1, b -> 3.2, c -> 4.5}**

Out[39]= 3.35127

In[40]= **{a, b, c}**

Out[40]= {a, b, c}

**Systems of equations** are handled by grouping the system with curly brackets

In[41]= **bun = 4 x - 7 y**

Out[41]= 4 x - 7 y

In[42]= **gun**

Out[42]= x + y

If both bun and gun take on specific numerical values, then that fixes the values of x and y. You can use Solve to sort that out.

In[43]= **Solve**[**{bun == 3, gun == 8}, {x, y}**]

$$\text{Out[43]}= \left\{ \left\{ x \rightarrow \frac{59}{11}, y \rightarrow \frac{29}{11} \right\} \right\}$$

If I substitute this solution back in to my function *bun*, I should get back the value I selected for it.



In[44]:= `bun /. %[[1]]`

Out[44]= 3

There is no limit to the number of equations you can include in your system, although you generally only need to include as many equations as you have variables.

■ Exercises

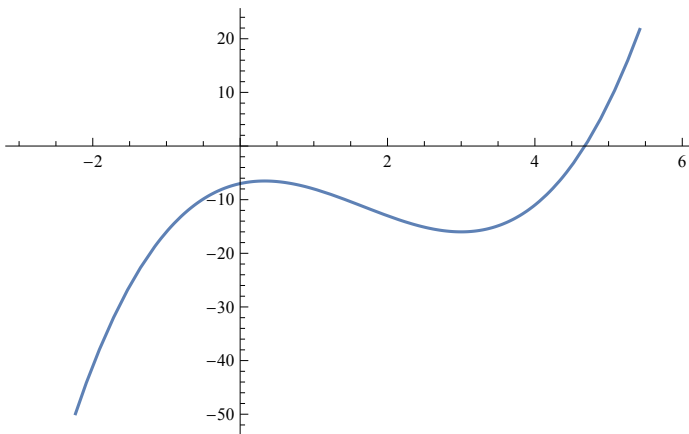
1. Solve the thin lens equation  $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$  for the image distance,  $q$ , in terms of the variables  $p$  (corresponding to the object distance) and  $f$  (the focal length of the lens). Call your solution for the image distance  $q$ , "image". Obtain an expression for the magnification (given by the equation  $mag = -q/p$ ) in terms  $f$  and  $p$  by substituting your solution "image" for  $q$ .
2. For a thin lens of focal length  $f = 20.0$ , find the image distance and magnification (the numerical values for *image* and *mag*) for an object located at the following positions:  $\{p = 10, 19, 21, 90\}$
3. For an image located at  $\{q = 30.0\text{ cm}\}$  and having a magnification of  $\{mag = -2.5\}$  find the corresponding object position,  $p$ , and focal length,  $f$ , of the lens. (Hint, solve for the system of equations. *Mathematica* will complain about the approximate values used.)

## Plotting and Visualizing the Results

Solve provides specific solutions for specific inputs, or else gives an expression as the output. Sometimes, that is good enough. Sometimes, it is really nice to see a graphical representation of the solution to summarize the results in one picture. For this, *Mathematica* provides the user with a great number of tools. The most basic one is simply `Plot[expression, range]`. An expression is usually a function of one or more variables, such as the third order polynomial function I called "tun" earlier. The range is simply the range of values for which I wish to plot the function. With trial and error, I find that the range from -3 to 6 is interesting. So I type the command:

In[45]:= `Plot[tun, {x, -3, 6}]`

Out[45]=



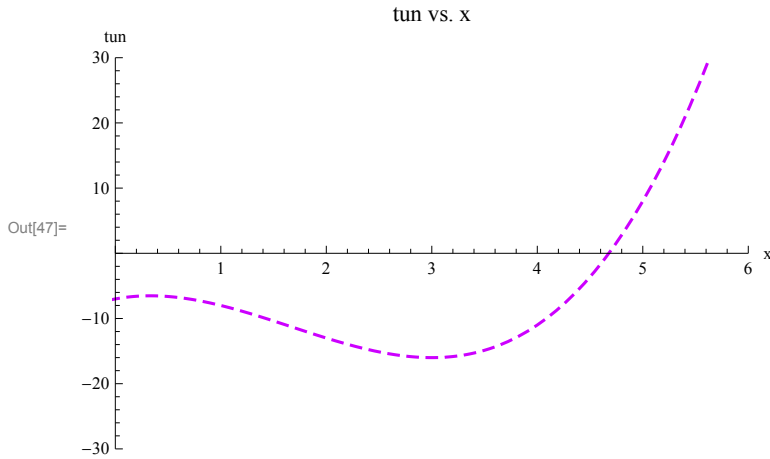
In[46]:= `tun`

Out[46]=  $-7 + 3x - 5x^2 + x^3$

See the zero at  $\sim -4.67$  that we found using `Solve` earlier? The meaning of the complex roots is seen here in that although the function changed directions three times and could have crossed the x-axis three times, it only crosses once (the real root). To see the other two roots, you need to look at the function in imaginary space. By default *Mathematica* only shows you the most interesting part of the function, in the part of the range where it undergoes the most change. You may have to adjust that.

There are lots of options with `Plot`. These options are also Commands (and must be capitalized), and are placed in the slots after the first two mandatory slots for the expression to be plotted and the range of the variable. Unless you want to set their values permanently, you should use rules to set them for the particular graph you are making. Here I show you just a few.

```
In[47]:= Plot[tun, {x, -3, 6}, AxesLabel -> {"x", "tun"}, PlotRange -> {{0, 6}, {-30, 30}},
PlotStyle -> {AbsoluteDashing[{5, 5}], Hue[.8]}, PlotLabel -> "tun vs. x", PlotPoints -> 100]
```



*PlotRange* fixes the extent of the axes in first the horizontal, and then vertical directions. If you don't do this, *Mathematica* will often focus on the interesting part of the function, but may miss what you wish to look at.

*PlotStyle* allows you to change how the lines for the different plots look.

*Axes-* and *PlotLabel* are obvious.

*PlotPoints* is a way to force *Mathematica* to plot more carefully and in detail. It usually doesn't miss interesting behavior, but if there are a lot of fluctuations, it can miss things. You can demand that it plot a certain number of points over the range of the graph.

You can plot multiple expressions of the same variable by grouping them in the first slot of the *Plot* command using curly brackets.

One very useful command that can be used with the *Plot* command is *Manipulate*. This command allows you to see at a glance what happens to the plot by varying one of the variables in the expression. Let's refer once again to the thin lens equation,  $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$ .

```
In[48]:= Solve[1 / p + 1 / q == 1 / f, q]
```

$$\text{Out[48]= } \left\{ \left\{ q \rightarrow -\frac{f p}{f - p} \right\} \right\}$$

Again, I will give this solution a name, *image*, but instead of leaving it as a variable, I will define it as a function of the variables *p* and *f*

```
In[49]:= image[f_, p_] = q /. First[%]
```

$$\text{Out[49]= } -\frac{f p}{f - p}$$

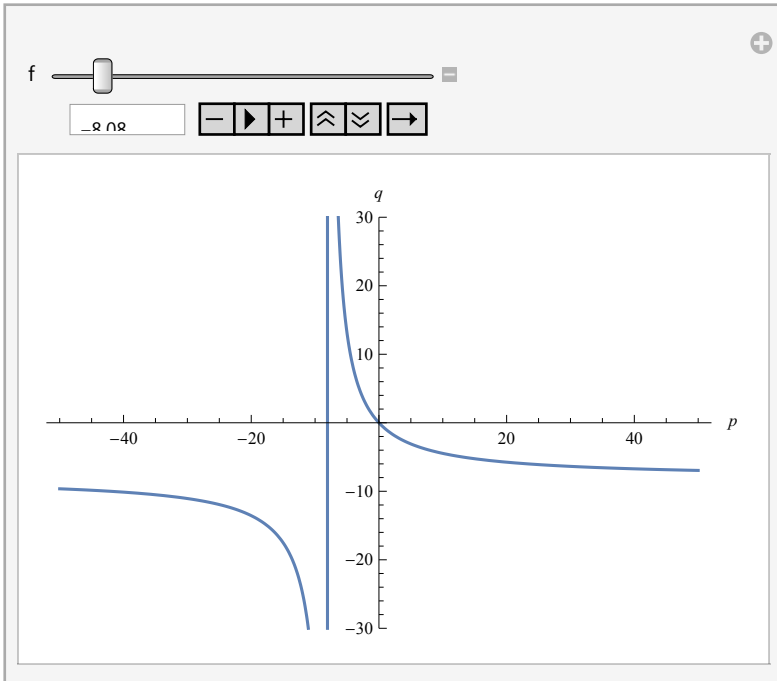
It is usually necessary to define functions this way when you want to plot a function of two or more variables. The underscore is necessary if I want to leave the names of the variables undetermined. Whatever value or variable is put into that first slot takes the place of "f" in the definition of the function "image".

```
In[50]:= {image[w, c], image[39, 54]}
```

$$\text{Out[50]= } \left\{ -\frac{c w}{-c + w}, \frac{702}{5} \right\}$$

Now we are ready to see what we can do with the *Manipulate* command.

```
In[51]:= Manipulate[Plot[image[f, p], {p, -50, 50},
    PlotRange -> {All, {-30, 30}}, AxesLabel -> {p, q}], {f, -10, 10}]
```



By sliding the bar to the right, I can see how the image distance varies with the object distance as  $f$  changes from a negative number (a diverging lens) to a positive one (converging lens). This is a great tool for seeing what would happen to the image as you change the focal length of the lens, like the optometrist might change it by switching the lenses with his machine to test which prescription is best for you. You can see the value of  $f$  you have chosen by clicking on the plus sign at the end of the sliding track.

■ Exercises

1. Plot the following expressions involving the variable  $x$ :  $\{x^2 + 3x - 2, \text{Cos}[x^2], \text{Log}[x^5 + 3 x^3]\}$
2. Recall that the equation for the position as a function of time of a uniformly accelerated object is  $x[t] = x_0 + v_0*t + 1/2 a*t^2$ , where  $x_0$  is the initial position,  $v_0$  is the initial velocity, and  $a$  is the acceleration. Define your position to be a function of time plus the initial values. That is, let  $x[t] = \text{pos}[t, x_0, v_0, a]$ , and make a plot of the position of the object as a function of time,  $t$ , for the values of the parameters  $\{x_0 = 2.0, v_0 = -5.0, a = 5.0\}$ .
3. Using your expression for position obtained above, create a manipulatable plot that allows you to see how the position vs. time will change as you vary the acceleration from  $-2 \text{ m/s}^2$  to  $10 \text{ m/s}^2$ . Use  $\{x_0 = 2.0, v_0 = -5.0\}$ .

## Conclusion

I hope this lab has given you a taste of the power *Mathematica* brings to your study of physics, chemistry and many other sciences. And we haven't even touched on its ability to do calculus. ~~That'll come next week!~~

## Lab 2: Electrostatic Simulations Using Interactive Physics

You used Interactive Physics last fall to simulate a number of mechanical phenomena. You will use it in this laboratory exercise to simulate Coulomb's Law and electric field phenomena.

In each part of this section of the laboratory exercise, you will be asked to set up a simulation. Then, before running the simulation, you are to make a written **prediction** about what will happen when you RUN the simulation. The prediction should focus on the accelerations (magnitudes and directions) of each object involved in the simulation. **You should predict how large the initial magnitude of the acceleration of each object will be as well as the direction of each acceleration (a sketch would be helpful in giving the directions). In addition, you should state whether the acceleration of each object will remain constant, increase, or decrease during the simulation.** You must also show how you derived your predictions from the fundamental principles of electrostatics and mechanics -- in particular, Coulomb's Law and Newton's Second Law.

In the first part of each section, a correct sample prediction will be given. Use these sample predictions as guides in writing your own predictions for the other parts.

After making your prediction, you should RUN the simulation and **observe** and record what actually happens. Write down the initial magnitudes and directions of each acceleration and describe how they change as the simulation progresses.

Finally, if a prediction differs from an observation, you should **resolve** the differences.

Discuss what mistakes you made in deriving your initial prediction and explain what actually happened based on Coulomb's Law and Newton's Second Law.

Your grade will not be reduced for an incorrect prediction as long as you make a correct observation and properly explain the outcome in the resolution section.

### a) Coulomb's Law

This part of this laboratory exercise will deal with systems of two or more point charges.

Start the Interactive Physics program. Open the Interactive Physics program and in the **VIEW** menu select Workspace. Turn on Rulers, Grid Lines, XY Axes, and Coordinates. The solid lines you see are the X and Y axes -- the Y axis is vertical and the X axis is horizontal. The X and Y coordinates of the mouse pointer are given in meters at the bottom of the screen. This can be helpful in determining the position of various points on the path of a charged object. If the origin of the XY system is not in the center of the screen use the Scroll Bars to move it there.

Create two circular objects (Click circle on the side menu bar). Right click on the created circle and use the Properties Window to place them at the following coordinate locations: (-.5 m, 0), (+.5 m, 0). Make sure that the diameters of the two charges are small enough so that they do not touch when they are in their initial positions. Use the Properties Window to assign masses of

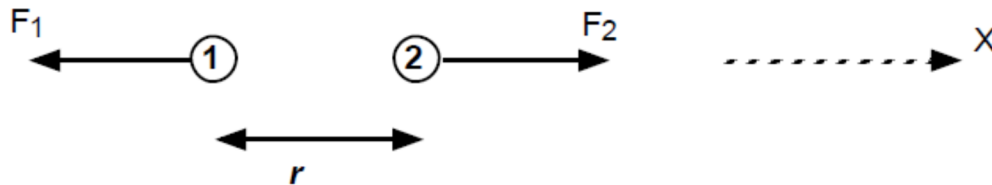
10 kg. to each object. Note that Interactive Physics automatically assigns a charge of  $+100\mu\text{C}$  to each object you create. Do not change these charges until you are told to do so. To **create an acceleration meter for each object, click on the object. Once you have chosen the object, click Define  $\rightarrow$  Vectors  $\rightarrow$  Acceleration. Then click Measure  $\rightarrow$  Acceleration  $\rightarrow$  All.**

Go to the **WORLD** menu, select **Gravity**, and turn gravity off by selecting “none”. Select **Electrostatics from the World menu and turn it on.** With these changes, your objects will feel only electrostatic forces.

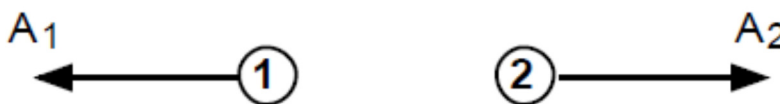
i) **Equal charges, equal masses** ( $Q_1 = Q_2 = 100\ \mu\text{C}$  ,  $M_1 = M_2 = 10\ \text{kg}$ .)

The simulation you have created has two equal mass objects with equal positive charges.

**Predict (This part should be written in your lab notebook)**



The X axis is directed to the right and the charge on the left will be called charge #1. The fact that like charges repel determines the directions of the forces on each charge. By Newton’s Second Law, the acceleration of an object will be in the same direction as the force on the object. Thus, the acceleration directions will be as follows:



The initial magnitudes of the forces are given by Coulomb’s Law:

$$F_1 = F_2 = \frac{kQ_1Q_2}{r^2} = \frac{(8.99 \times 10^9)(100 \times 10^{-6})(100 \times 10^{-6})}{(1.00)^2} = 89.9\text{N}$$

The **magnitude of the initial acceleration** of each object is determined using Newton’s Second Law:

$$A_1 = F_1/M_1 = (89.9)/(10) = 9.0\ \text{m/s}^2$$

$$A_2 = F_2/M_2 = (89.9)/(10) = 9.0\ \text{m/s}^2$$

As time passes, the distance between the two charges will increase, which will cause each force to decrease. The **accelerations will thus decrease.**

**Simulation:** Run your simulation. Use STOP and RESET buttons to replay the simulation. Use the slide bar or arrows on the left bottom of the screen to view snap shot of the scenarios.

**Observe** (Record your observations in your lab notebook.)

**Resolve** (If your observation agrees with your prediction, you don't need to write anything in the resolve section of your lab notebook).

ii) **Unequal charges, equal masses** ( $Q_1 = 200 \mu\text{C}$ ,  $Q_2 = 100 \mu\text{C}$ ,  $M_1 = M_2 = 10 \text{ kg}$ .)

Use the Properties window to double the charge of one object. Use the same initial positions of the two objects that you used in part i).

**Predict** (Be sure to give reasons, based on the laws of physics, for each part of your prediction.)

**Observe**

**Resolve**

iii) **Equal charges, unequal masses** ( $Q_1 = Q_2 = 100 \mu\text{C}$ ,  $M_1 = 20 \text{ kg}$ ,  $M_2 = 10 \text{ kg}$ .)

Make the charges the same but double one of the masses.

**Predict**

**Observe**

**Resolve**

iv) **Opposite charges, equal masses** ( $Q_1 = -100 \mu\text{C}$ ,  $Q_2 = + 100 \mu\text{C}$ ,  $M_1 = M_2 = 10 \text{ kg}$ )

Make the masses the same but make the charges equal and opposite (e.g., one positive and one negative)

**Predict**

**Observe**

**Resolve**

v) **Oscillator**

Use two equal positive charges ( $100 \mu\text{C}$  each,  $10 \text{ kg}$ . each) that are anchored (Use anchor symbol from the menu) in place  $(-4.0, 0, 4.0, 0)$  and a third positive charge (same charge and mass of the anchored charge) that is free to move to create an oscillating system. Determine the equilibrium position (the location where the third charge will not move if it starts at rest). Is it a simple harmonic oscillator for small displacements from equilibrium? Create a position graph.

For this, after clicking on the third object, open X position graph from **measure** icon. Then examine position graph to determine if the motion is simple harmonic. **Measure the period and frequency of the oscillation using the position graph.** [Be sure to record the details of your oscillator. Draw a sketch showing the locations and value of each charge.] **Let the instructor see this part when you have it working.** Now repeat the experiment by increasing the oscillating charge to 200  $\mu\text{C}$ , keeping mass of the oscillating charge at 10 kg. Next increase mass to 20 kg and keeping charge to 100  $\mu\text{C}$ .

## b) Electric Fields

In this part, you will observe the interaction between one or more point charges and an external electric field.

Go to the WORLD menu and turn Electrostatics off. Select **Force Fields** from the WORLD menu. Leave the Sample Force box at "Custom". Select the "Field" button from the three buttons in the upper left hand corner of the window. In the Fx box type the following:

**self.charge\*10000**

Leave the Fy and T (torque) boxes empty. You have created an electric field of magnitude 10000 N/C in the x-direction (the x-direction is to the right). This field now exists throughout the Interactive Physics universe.

i) **Q, M** ( $Q = 100 \mu\text{C}$ .,  $M = 1.00 \text{ kg}$ )

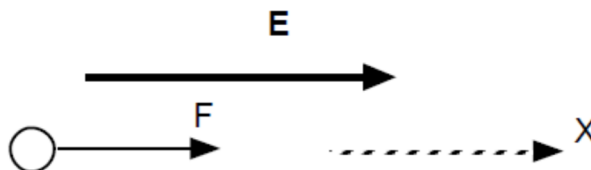
Create a single object of charge  $+100\mu\text{C}$  and mass 1 kg, and place it at location (0,0). Create an acceleration meter for this object. Once you have chosen the object, click Define  $\rightarrow$  Vectors  $\rightarrow$  Acceleration. Then click Measure  $\rightarrow$  Acceleration  $\rightarrow$  All.

### Predict

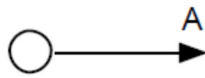
The following equation relates the electric force on a charged particle to the electric field acting on it:

$$\mathbf{F} = Q\mathbf{E}$$

where  $\mathbf{F}$  is the electric force vector and  $\mathbf{E}$  is the electric field vector. Since  $Q$  is positive,  $\mathbf{E}$  points in the same direction as  $\mathbf{F}$  as shown in the figure below:



The acceleration vector thus points to the right as shown in the figure below:



The magnitude of the electric force acting on the particle is found as follows:

$$F = QE = (100 \mu\text{C})(1 \times 10^4 \text{ N/C}) = 1.00 \text{ N}$$

The acceleration is found from Newton's Second Law

$$A = F/M = (1.00 \text{ N})/(1.00 \text{ kg.}) = 1.00 \text{ m/s/s}$$

**Observe**

**Resolve**

ii) **2Q, M** ( $Q = 200 \mu\text{C.}$ ,  $M = 1.00 \text{ kg}$ )

Double the charge of the object and predict how its acceleration will compare with that of the Q, M object.

**Predict**

**Observe**

**Resolve**

iii) **Q, 2M** ( $Q = 100 \mu\text{C.}$ ,  $M = 2.00 \text{ kg}$ )

**Predict**

**Observe**

**Resolve**

iv) **-Q, M** ( $Q = -100 \mu\text{C.}$ ,  $M = 1.00 \text{ kg}$ )

Make the charge negative

**Predict**

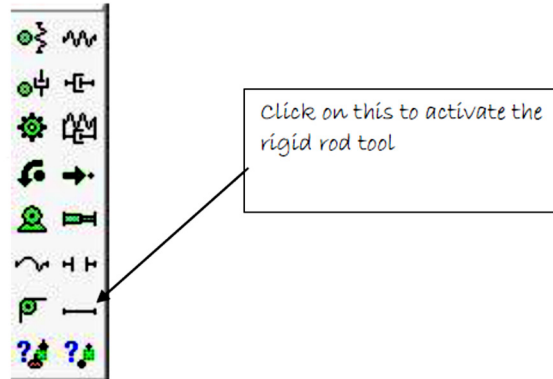
**Observe**

**Resolve**

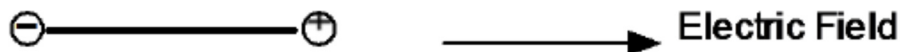
v) **Dipole**



Delete the object used above and create an electric “dipole”. This is done by creating two objects  $(-0.5, 0)$  and  $(+0.5, 0)$  of equal mass (1.00 kg. each) and equal but opposite charges  $(-100 \mu\text{C}$  and  $+100 \mu\text{C})$  and connecting them with a rigid rod of length 1.00 meter. The rigid rod tool is activated by pointing the mouse at the tool shown at the left below, clicking on it and releasing the mouse button. Connect the rigid rod from the center of one object to the center of the other.



Orient the dipole as shown below and predict what will happen to it. In particular, **will the center of mass of the dipole accelerate?** If so, in what direction will it accelerate and what will be the magnitude of the acceleration? Will the dipole rotate? If so, in what direction? (Be sure to give reasons for your predictions based on the fundamental principles of electrostatics and mechanics.) [Note that the force of attraction between the two charges of the dipole is exactly canceled by the compressive forces exerted by the rod. Thus, the sum of the internal forces of the dipole is zero and only the external forces (i.e., the forces exerted on the two charges by the electric field) have any effect on the motion of the dipole.]

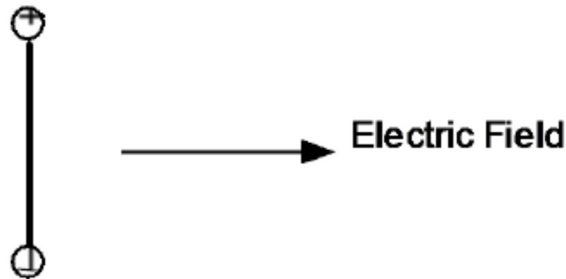


**Predict**

**Observe**

**Resolve**

Now orient the dipole as shown below. Will the center of mass of the dipole accelerate? If so, in what direction will it accelerate and what will be the magnitude of the acceleration? Will the dipole rotate? If so, in what direction? (Be sure to give reasons for your predictions based on the fundamental principles of electrostatics and mechanics.)



**Predict**

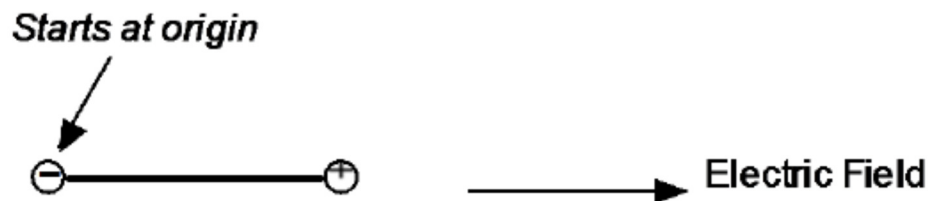
**Observe**

**Resolve**

You will now change the electric field so that it increases in the X direction. Go to the WORLD menu and select **Force Fields**. Click the “Field” button and in the Fx box type the following:

**self.charge\*10000\*self.p.x**

The field now has the functional form  $10000X$ . Orient the dipole as shown below and be sure that the negative charge is initially located at the origin. Will the center of mass of the dipole accelerate? If so, in what direction will it accelerate and what will be the magnitude of the acceleration? Will the dipole rotate? If so, in what direction? (Be sure to give reasons for your predictions based on the fundamental principles of electrostatics and mechanics.)



**Predict**

**Observe**

**Resolve**

You will now make predictions about the motion of an electric dipole near a point charge. (Use a point charge of  $+100 \mu\text{C}$ .) Turn off the electric field used above (open the *World* menu, select *Force Field*, and select the *OFF* button.) Turn on Electrostatics. Set up the simulation shown below:

*Anchor this charge  
in place*



Will the dipole move? If so, in which direction will it move? Give reasons for your prediction.

**Predict**

**Observe**

**Resolve**

## Lab 3: Electric Field and Potential Measurements

### Equipment:

1. Power Supply – 0-24 volts
2. DMM (orange)
3. Sets of connecting wires and alligator clips
4. 3 conducting papers with point/plane, plane/plane with a conductor in the middle, and a dipole
5. All accessories

### Introduction

In this laboratory experiment, you will examine the electric fields produced by three different charge configurations:

- a) **A point charge and a charged plane**
- b) **Two charged planes with an uncharged conducting sphere between them**
- c) **Two point charges (one positive, one negative)**

It is not practical to establish electric fields in the laboratory using actual charged objects. There are two reasons for this: 1) charge will leak from the objects, causing the fields to change before the measurements can be completed and 2) electric field measurements for this type of system require instruments that are expensive and difficult to use.

Rather than using charged objects, we will use conductive papers on which three-dimensional versions of the objects are placed. One of the objects will be connected to the negative terminal of a DC power supply and the other object will be connected to the positive terminal. Electrical currents will flow in the paper from the positive object to the negative object. The electric fields associated with these currents in the paper are *identical* to the fields that would exist in a two-dimensional plane containing the actual charged objects. It is not too wrong to think of the flow of electric current in the paper as being like the electric flux.

The electric field cannot be measured directly. Instead, you will measure the potential (also called voltage) of a large number of points on the paper (relative to the grounded surface) using a voltmeter and plot these points on a piece of graph paper. Points of equal potential will then be connected by curves called “**equipotential lines**”. (Note that these “lines” are usually curved and not straight.) The **electric field lines** will then be drawn using the rules that **1) they are always perpendicular to the equipotential lines and 2) they start from positive charges and end on negative charges**. (The object connected to the positive terminal of the battery is considered to be the positively charged object while the object connected to the negative battery terminal is the negatively charged object.)

The above procedure will be used for charge configurations a), and b). You will then make a three-dimensional surface graph of the potential for configuration c) using a spreadsheet. The

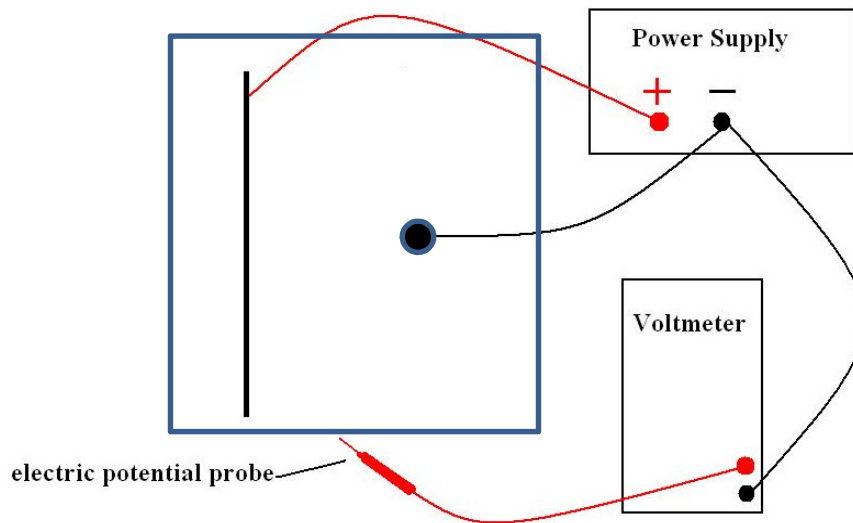
slope of the three-dimensional graph at any point will be used to determine the electric field vector at that point.

## Procedure

### a) A point charge and a charged plane

Turn on the voltmeter and let it warm up. Make sure it is set to the 20-volt range and that its function switch is set to DC.

Place the conductive sheet for configuration a) on the fiberboard tray (Figure) and put nuts and bolts specific to that configuration. Use alligator clips (one object is the point charge and the other is the plane) to connect the positive terminal of the power supply to the object you want to be positive and to connect the negative terminal to the negative object. Set the voltage on the power supply to 2 V. The ground lead of the voltmeter should be connected to the pin in the negative object. Be careful not to touch the paper with your hands more often than necessary -- the moisture on your hands may alter the conductivity of the paper. Please note here a “point charge” should have about 2-cm diameter at least, otherwise the voltage is not well defined near the charge.



When the voltmeter probe is touched to a point on the paper, the voltmeter will read the potential of that point. The potential of the object connected to the ground lead (the negative object) should be zero volts. Touch the probe to that object and see if it has a potential of zero volts. Then touch the probe to the positive object and see if its potential is 2 volts. Now touch the probe to various points between the two objects and see if the voltmeter reads voltage values between 0 and 2 volts. Ask your instructor for help if the system isn't functioning properly.

You are now ready to make a potential map of the first configuration. [Note that there is a sample potential map on page 6, though it is for the case of charges on two perpendicular planes]

Using a sheet of graph paper in your lab notebook (be sure to use a full page per map), establish an origin and X and Y axes identical to those on the conducting paper (your graph should be a smaller size image of the conducting paper). [*The conducting paper has a coordinate system printed on it. The origin is in the lower left hand corner; the X-axis is along the bottom edge of the paper and extends from the origin to 28 cm; and the Y-axis is along the left hand edge of the paper and extends from the origin to 20 cm. You can identify any point on the paper by giving its X and Y coordinates.*] Sketch the point charge and the plane in their proper positions and label them with their potential values (one will be 0 volts and the other will be 2 volts). Now use the voltmeter probe to find a point along the center line (the line whose Y-coordinate is 10 cm) that has a potential of 0.4 V. Mark that point with white ink on the conducting paper. Plot this point on your graph also and label it 0.4. Now find other points that also have potentials of 0.4 V. Mark them with white ink as well as plot them on your graph and label them 0.4. When you have enough of these 0.4 V points, you will see that they can be connected by a smooth curve -- an **equipotential line**. Draw the 0.4 V equipotential line. Note that for some potential values the equipotential lines will form closed curves, for others they will not. (If the paper were large enough, all equipotential lines would be closed.) When measuring the potential, avoid touching the conductive paper by your hand.

Use the procedure described above to draw the equipotential lines for at least 5 different voltages (0.4 V, 0.8 V, 1.2 V, ...) Some equipotential lines require just a few points to determine their shape; others may require more points.

On the potential map you have constructed, draw electric field lines (the number of lines drawn should be between seven and ten). ***Remember that field lines start on positive charges and end on negative charges and that they are perpendicular to equipotential lines. Be sure to draw an arrow on each electric field line indicating the direction of the field (electric fields point from positive to negative charge).***

### **b) Two charged planes with an uncharged conducting sphere between them**

Construct a potential map and draw electric field lines for configuration b) two charged planes and an uncharged conducting sphere between them. For this case, connect the battery to each of the planes but **not** to the sphere -- this causes the sphere to be uncharged. Be sure to measure the potential of points on the sphere and inside the sphere. Look carefully at the region surrounding the sphere when measuring potential and when drawing the field lines.

### **c) Two point charges: three-dimensional potential maps**

You will now make a three-dimensional surface map of the electrical potential for configuration c). [A three-dimensional map for configuration (a) (two point charges) is on page 8-8.] Open an EXCEL spreadsheet and in the first row enter the numbers 0, 2, 4, 6, ..., 28. This row contains the X axis scale markings. In the first column enter the numbers 0, 2, 4, ..., 20. This column contains the Y axis scale markings. To make all of your data visible on the screen, select

all of the cells on the spreadsheet (you can do this easily by clicking on the point where the row header and column header come together), choose *Column Width* from the *Format* menu, and enter a column width of 4. The spreadsheet should now look like the following:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28
2	0															
3	2															
4	4															
5	6															
6	8															
7	10															
8	12															
9	14															
10	16															
11	18															
12	20															

Now place the voltmeter probe at the point (0, 0) on the conductive paper. Enter the voltmeter reading in the cell corresponding to  $X = 0$  cm and  $Y = 0$  cm. Repeat for all of the other spreadsheet cells.

Select all of the data in the spreadsheet (including the first row and column) and then click on the Insert tab, and then select the Recommended Charts icon, and choose the All Charts tab. Select the Surface chart on the left, and then select the *3-D Surface graph*. Use an appropriate description of the charge configuration for the Chart Title. You will need to select the graph and then click on the Plus Sign to the right where you can edit or add Chart Elements, and click the box for Axis Title to show boxes for axes titles. For the axis titles let the horizontal axis be X, let the axis going into the paper be Y and let the vertical axis be V (for voltage). Select FINISH and you should now see a three-dimensional surface graph of the electrical potential inserted on to your worksheet.

Right click on the chart and select 3-D Rotation. A window will open off to the right on your spreadsheet that allows you to change the X rotation, Y rotation, and perspective of your graph. Adjust the view so that you get the best picture of the potential graph. You can make other changes in the graph using selections from the CHART menu.

The magnitude and direction of the electric field at a given point can be determined by examining the slope of the three-dimensional surface graph of the potential at that point. Imagine that you were standing on the potential surface. You try to determine the slope by measuring the change in height of the surface as you move a given distance from the point. You quickly notice that the slope of the surface will depend on the direction in which you move. The electric field

vector will point in the direction that gives the maximum negative slope of the potential surface. The magnitude of the electric field vector is the absolute value of the maximum negative slope.

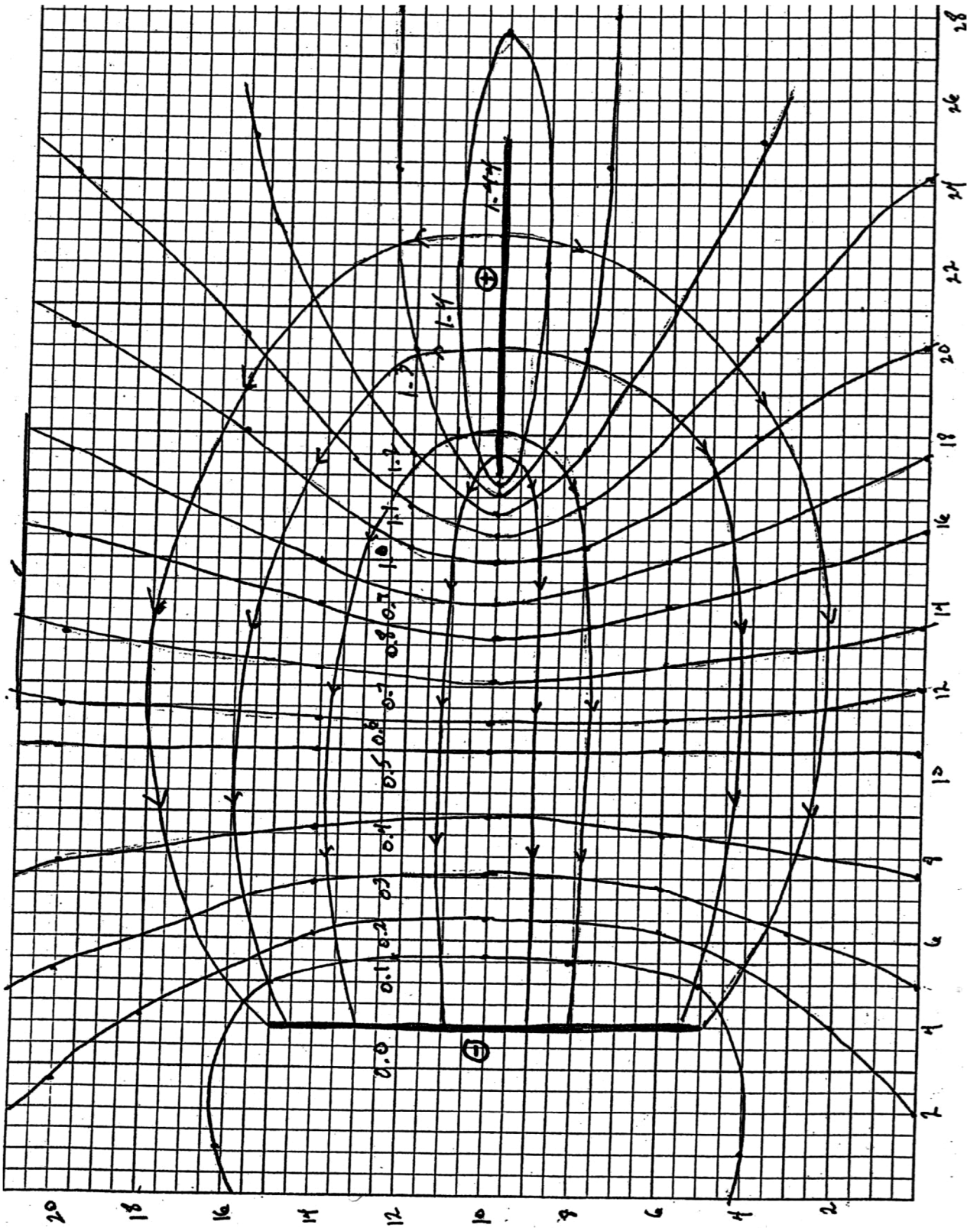
Print the chart and your worksheet, and then sketch the electric field lines on your chart.

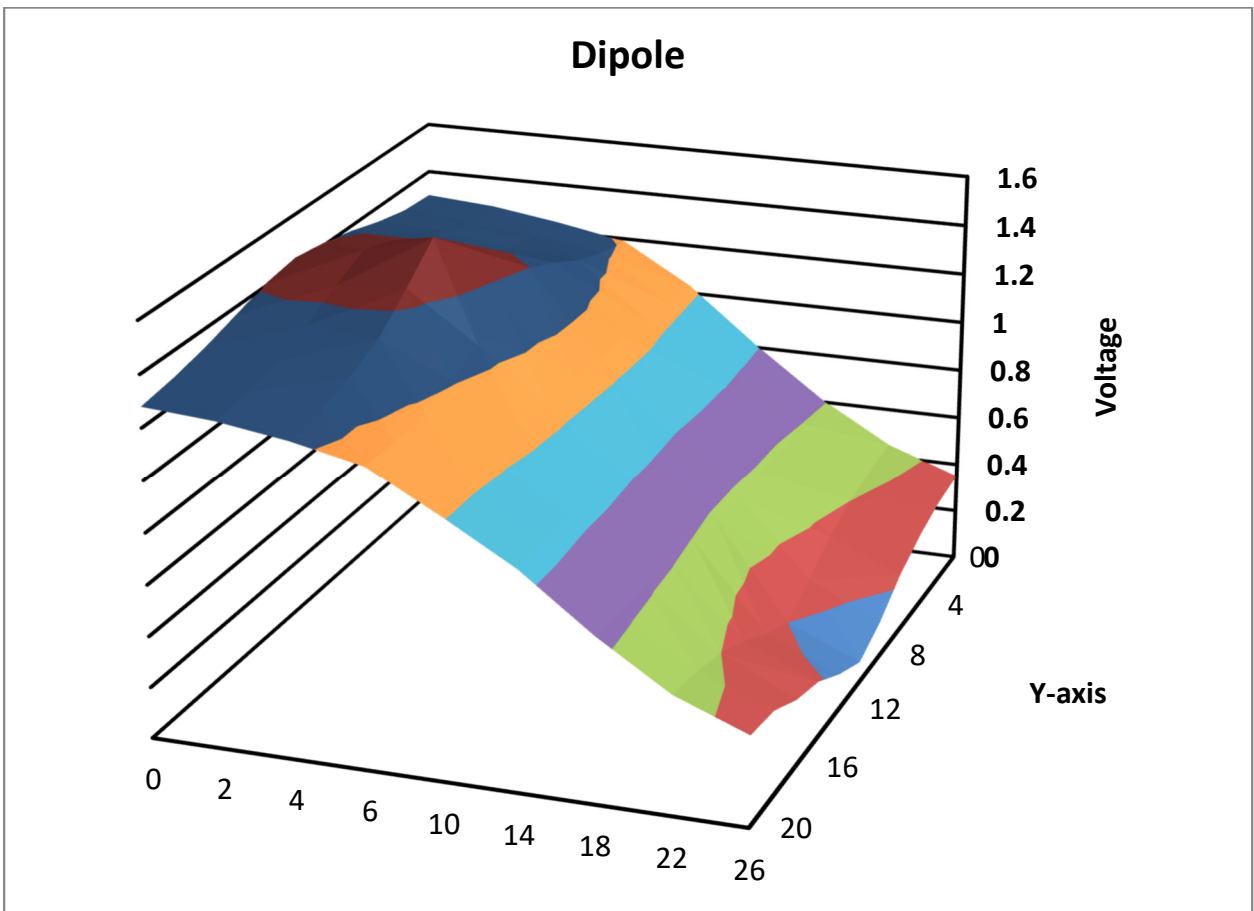
### Questions

1. For the electric potential difference of 1.4 V along the straight line between the two point charges, calculate the magnitude of the electric field using the equation  $\Delta E = \frac{\Delta V}{\Delta x}$ .

2. For the electric potential difference of 0.6 V along the straight line between a plane and a point charge, calculate the magnitude of the electric field using the equation  $\Delta E = \frac{\Delta V}{\Delta x}$ .







## Lab 4: Capacitors

### Equipment:

1. Low voltage DC/AC power supply
2. Three 47  $\mu\text{f}$  capacitors
3. 1 DMM
4. LCR hand held meter
5. **Differential voltage probe**
6. Logger pro
7. Parallel plate capacitors (Aluminum)
8. 5 transparent sheets
9. Vernier Calipers
10. Cylindrical aluminum capacitor (homemade)
11. Connecting wires and alligator clips
12. Bread board

### I. Capacitors and Dielectrics

#### a) Parallel Plate Capacitors

The capacitance of a parallel plate capacitor is given by the following equation:

$$C = \frac{K\epsilon_0 A}{d}$$

where  $K$  is the dielectric constant,  $\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N}\cdot\text{m}^2$ ,  $A$  is the area of the plates, and  $d$  is the separation distance between the plates. You will examine the effect of area and distance on capacitance using a capacitor made of two pieces of aluminum separated by sheets of plastic. You should be able to verify the general dependence of  $C$  on  $A$  and  $d$ .

Take the two pieces of aluminum and one sheet of plastic and build a parallel plate capacitor. Sandwich the plastic between the aluminum plates and make sure that one plate is directly on top of the other. Connect the wires from the LCR meter (set to measure capacitance) to the two screws in the aluminum plates. [Be careful not to let any part of the lower plate touch any part of the upper plate.] Observe the capacitance value (it should be in the neighborhood of 1 to 3 nanofarads,  $1 \text{ nF} = 1 \times 10^{-9} \text{ farad}$ ). Now while watching the meter, apply pressure to the upper plate. The capacitance value changes. Does it increase or decrease? Can you explain this change?

You now see why it is difficult to obtain reliable quantitative results for this type of capacitor -- the value of  $d$  is not simply the thickness of the plastic but also includes the thickness of the air spaces on either side of the plastic. Put a weight on top of the upper plate. This will press the

capacitor together, reduce the air spaces, and allow us to obtain more reliable measurements. Allow 15-20 seconds for the capacitor to compress and then observe the value of the capacitance. Record the capacitance value. You will now add 4 additional sheets of plastic (for a total of 5) and measure the capacitance. Based on the capacitance equation, what do you predict the capacitance will do -- increase or decrease, and by how much? Add the plastic and measure the capacitance.

Now, keeping the 5 sheets of plastic between the plates, slide the upper plate across the lower one until the overlap area is one half of the area of a single plate. Observe the value of the capacitance. Does the change in capacitance correspond to the change in area? Try other values of the area, and record your results.

## b) Cylindrical Capacitors

The capacitance of a cylindrical capacitor is given by the following equation:

$$C = K \frac{2\pi\epsilon_0 L}{\ln(b/a)}$$

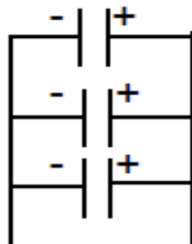
where  $K$  is the dielectric constant,  $L$  is the length of the cylinder,  $b$  is the radius of the outer cylinder and  $a$  is the radius of the inner cylinder.

You will be given a cylindrical capacitor made of aluminum foil wrapped on the outside and inside of a plastic pipe. Use Vernier calipers to measure the inner and outer diameters of the cylinder. Calculate the dielectric constant,  $K$ , of the plastic tube in your capacitor, and then compare your measured value to the reported value of plastic ( $K \sim 3$ ). Does your measured value of  $K$  for the plastic come near the expected value?

## II. Combinations of Capacitors

### a. Equivalent Capacitance

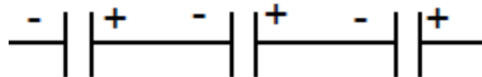
#### Capacitance in parallel



Next, measure the capacitance of each of the three  $47 \mu\text{F}$  capacitors. Label them as #1, #2, and #3. You will note that the measured values are not exactly the same as the labeled (nominal) values. This is a fact that you need to realize -- nominal values are not exactly the same as actual values. Often you may need measure the values of electrical components you are using, and use those measured values in all calculations.

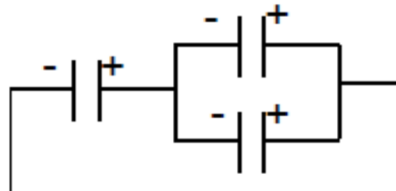
Using the concepts discussed in lecture and described in the text, predict the equivalent capacitance of the three capacitors when connected in parallel (be sure to use the measured values in your calculations). Using the breadboard (see page 7 for information on how to use the breadboard), connect the three 47  $\mu\text{F}$  capacitors in parallel. (Be sure that the negative sides of the capacitors are connected together.) Measure the equivalent capacitance (the capacitance of the entire combination) using the capacitance meter. How close does the actual value come to your prediction? They should be very close -- if not, find out what went wrong.

**Capacitance in series**



Repeat the above for the three capacitors in series. (Connect the positive side of each capacitor to the negative side of its neighbor.)

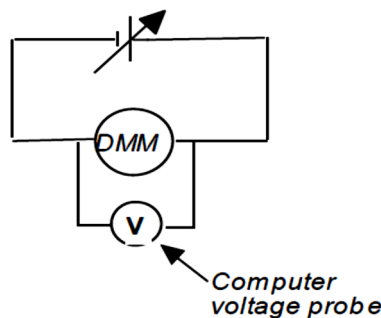
**Capacitance in series and parallel combination**



Now connect two of the capacitors in parallel and then connect this parallel combination to the third in series (a series-parallel combination). Measure the equivalent capacitance and compare with the theoretical prediction.

**b. Voltage measurements**

**Computer Measurement of Voltage**

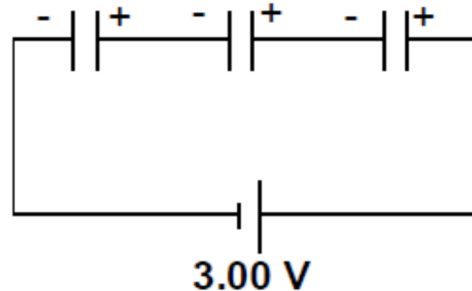


- Connect the DMM (set to function as a voltmeter) directly to the power supply.
- Open up the Logger Pro program on your computer.
- Once you have inserted the probe into the Lab Pro interface, check to see if the program has recognized the probe as a voltage probe connected to Ch. 1. If it hasn't, then you need to click on the icon for the Lab Pro interface and choose the "Voltage sensor – **Differential voltage**" for Ch. 1. Once the computer knows that this probe is connected, the program should insert a graph of Potential (V) vs. Time on the right of your screen (typically with a range from -5 to +5 volts), and also a Voltage meter in the lower left hand corner of your screen.
- Keep the voltage probe connected to the power supply, and continue to use the DMM to monitor the voltage of the power supply. Set the scale of the vertical axis of your graph from -5 to +5 volts, if it isn't already. Then, set the time duration of the experiment to 60 seconds by going to **Experiment->Data Collection**, and then setting the time duration to 120 seconds. Also, change the data rate in that same menu to 2 points per second.
- Disconnect the voltage probes from the power supply -- the Voltage 1 display should be 0. If it is not, click the zero icon button at the top of the graph window (If you do not see the zero icon, then click on **Experiment→Set up sensors→Show all interfaces→Ch 1→zero**). It is a good idea to check the zero of the voltage probes periodically to make sure the calibration hasn't "drifted" by a small amount.
- Reconnect the voltage probes. Press the COLLECT button and the computer will begin collecting voltage data and plotting it on the screen. Set the power supply to 2.50 volts (using the DMM). What is the computer voltage reading? (It will probably be close to, but not exactly equal to 2.50 volts. If the computer reading differs significantly from the DMM reading, let the instructor check the computer calibration.) Does the computer voltage reading remain steady or does it constantly change? A constantly changing reading is known as "jitter" and is normal for the type of computer data acquisition system we are using. [More expensive computer data acquisition systems would have a very small jitter.] With the power supply set at 2.50 volts, let the computer system take data for 120 seconds. A quantitative measure of the jitter can now be obtained by clicking on the **Statistics** button in the second row of the menu bar. Record the Min, Max, and Mean values. The difference between the Max and Min is the magnitude of the jitter. Divide the jitter magnitude by the Mean voltage reading and multiply by 100 to obtain the jitter as a percentage of the voltage reading.
- Change the power supply setting and see if the computer "tracks" (follows) the changes for voltages ranging from 0 to 5 volts.

## Voltage measurements across capacitors

### Capacitors connected in series

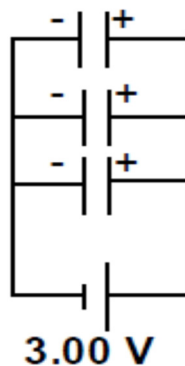
Predict what the voltage of each capacitor should be when they are connected as shown in the figure below. Connect the three  $47\ \mu\text{F}$  capacitors together in series as shown in the figure, but do not connect them to power supply at this time. Make sure that the polarity of the capacitors matches the polarity shown in the figure. Discharge each capacitor individually by briefly touching the two ends of a wire simultaneously to both sides of the capacitor (this allows any positive charge that might be on the capacitor to flow to the other plate and neutralize the negative charge). Now connect the capacitors to the power supply.



Measure the voltage across each capacitor using the voltage probe. How do your predictions compare with the actual measurements?

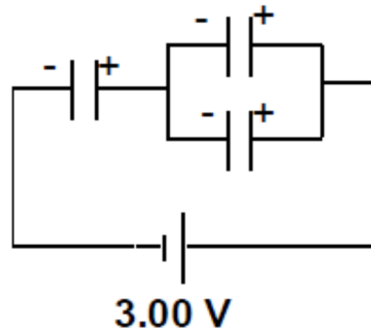
### Capacitors connected in parallel

Predict the voltage of each of the three capacitors when they are connected in parallel. Now connect the three capacitors in parallel, discharge each one, and connect the combination to the power supply as shown in the figure. Make the measurements and compare theory and experiment.



### Capacitors connected in Series-parallel combination

Now repeat the above with the series-parallel combination of the three capacitors shown in the figure.



### c. Voltage Multiplier

Connect the three capacitors in parallel, discharge them, and then charge them up by connecting them to the power supply. Disconnect the power supply and **quickly** reconnect the three capacitors in series (be sure that the positive side of one capacitor is connected to the negative side of the next). Measure the voltage of the three capacitors in series. (You must perform the above operation quickly because when a charged capacitor is disconnected from its charging source and connected to a voltmeter, it will lose its charge fairly rapidly.) If you could do this reconnection with zero elapsed time, you would find that the voltage across the three capacitors in series is three times the battery voltage. This process can be used to make a **voltage multiplier**. If you have  $N$  identical capacitors, you can multiply a given voltage by  $N$ .

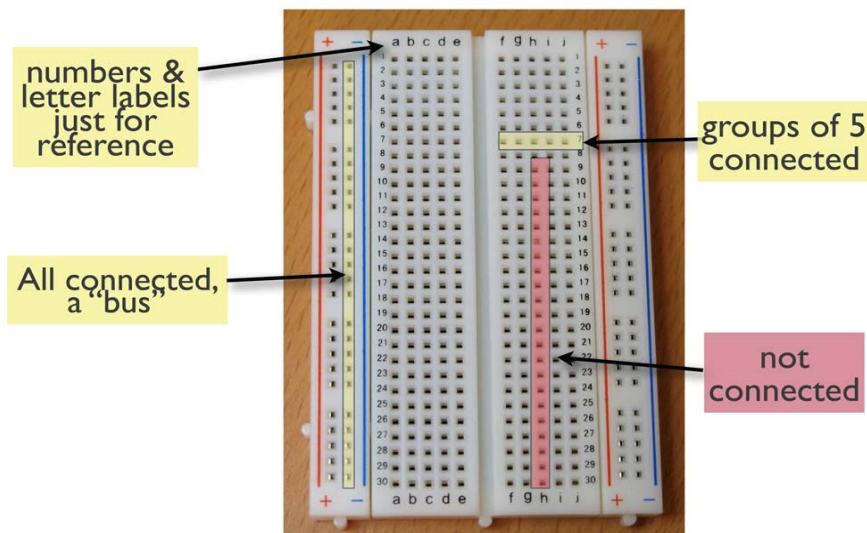


### The Breadboard

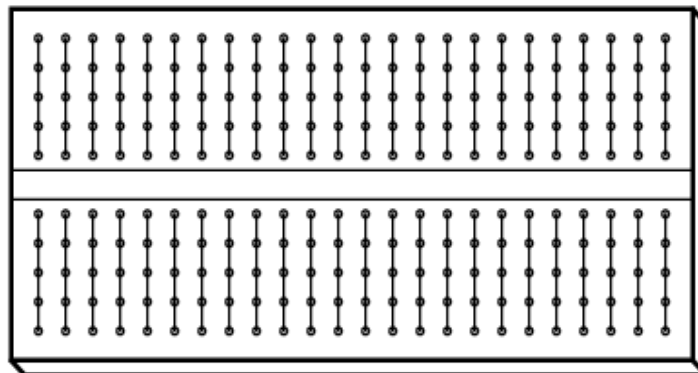
Breadboards allow us to make connections easily and quickly between a variety of electrical components -- resistors, capacitors, wires, switches, integrated circuits, etc.

Two electrical components can be connected together by inserting one of the lead wires from each component into one of the sockets in the same five-socket group. The connection is quick and solid and can easily be changed if needed. You can make as many breadboard connections on the breadboard as space will allow.

## Solderless Breadboards

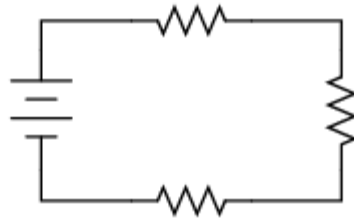


Lines show common connections underneath board between holes

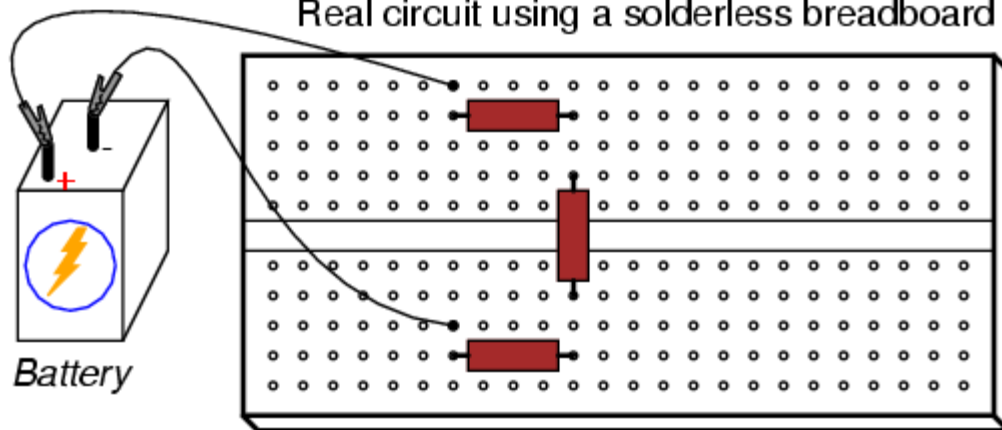


Here we show how an electronic circuit is realized on a breadboard.

Schematic diagram



Real circuit using a solderless breadboard



## Lab 5: DC Circuit I

### Equipment:

1. Low voltage DC/AC power supply
2. 2 DMMs (One grey and one orange)
3. Wire wound resistors 50  $\Omega$ , 100  $\Omega$
4. Carbon resistor 1000  $\Omega$
5. 1 Analog DC voltmeter (1.5/15/150 volt)
6. 1 Analog DC ammeter (15/150/500 mA)
7. A glass wet cell with ceramic cover with clamped metal electrodes (copper:zinc)
8. Dilute sulphuric acid
9. Dry cell
10. Voltage probe
11. Current probe
12. Logger pro
13. Connecting wires, alligator clips
14. Breadboard

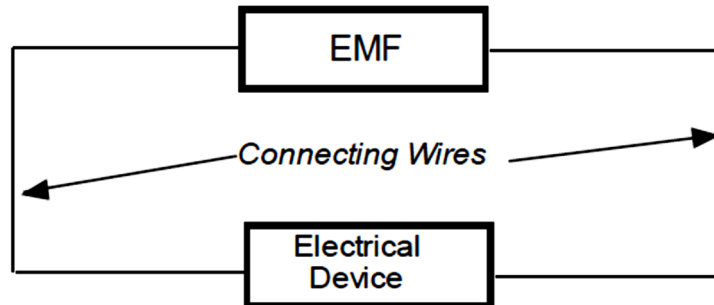
### Introduction

Electrical circuits play a fundamental role in the practical application of electricity and magnetism. If you spend a few minutes contemplating the ways in which electrical circuits affect your life, you will soon realize that modern civilization could not exist without them. We can group the applications of electrical circuits into several major categories:

- 1) **Energy Transfer** -- The potential energy stored in coal, oil, natural gas, flowing water, sunlight, etc., is transformed into electrical energy, which is then transported over power lines to a "user" where the energy is transformed into more usable forms such as light, sound, heat, and motion.
- 2) **Information Transfer** -- Information is transformed into electrical signals which are transmitted (over wires, fiber optic cables, or even through empty space) to a receiver where the signals are processed and the original information is recovered).
- 3) **Control** -- Electrical circuits are used to control the operation of a variety of devices -- e.g., door openers, water valves, airplane flaps, etc.
- 4) **Information Processing** -- Computers (from mainframes to micros) use electrical circuits to gather, analyze, store, and display information of all types.
- 5) **Scientific Analysis** -- Physical variables (such as velocity, acceleration, force, pressure, temperature) are often transformed into electrical signals which can then be analyzed by a variety of electrical instruments.

## Electrical circuits

A basic electrical circuit is shown below. All electrical circuits, no matter how complicated, contain the same fundamental elements as this one.



The EMF (Electromotive Force) is the source of electrical potential energy that drives the charge carriers through the circuit. It is connected by metallic wires to an electrical device (a light bulb, a carbon resistor, a motor, a loudspeaker, etc.) or several such devices connected together in some way. The strength of the EMF is called its potential difference or **voltage** and is measured in **volts**.

The EMF creates an electric field in the circuit that starts at the positive (high energy) side of the EMF and ends at the negative (low energy) side. This field exerts an electrical force on the charge carriers in the circuit and causes them to move through the circuit. This movement of charge is called electrical **current** and is measured in **amperes**.

The electrical devices oppose (or resist) the motion of electrical charge through them. The amount of this opposition is called the **resistance** of the device and is measured in **ohms**.

An electrical circuit can be thought of as an energy transfer system. The EMF puts energy into the current flowing through it and the current gives up this energy in the process of moving through the electrical devices. Energy is thus transferred from the EMF to the devices. The energy given up by the current as it passes through an electrical device is determined by measuring the potential difference or voltage between the ends of the device.

## Electrical circuit measurements

The fundamental quantities used in describing and analyzing DC circuits are **voltage**, **current**, and **resistance**. Measurements of these quantities are made using various types of electrical instruments. Voltage is measured by a voltmeter, current by an ammeter, and resistance by an ohmmeter. Some meters are devoted entirely to making measurements of one of the above quantities. Other meters can make measurements of two or more of the quantities and are called multimeters.

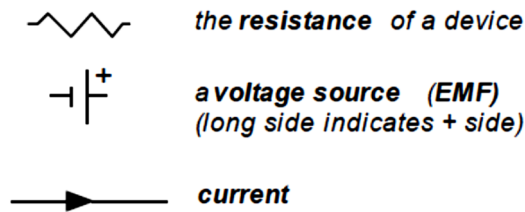
Meter readouts may be digital or analog. **Digital** scales are read directly. **Analog** scales are generally estimated to 1/10 of the smallest scale division. When recording a meter reading, give

the **magnitude** of the measurement to the correct number of significant figures as well as the **unit** of the measure.

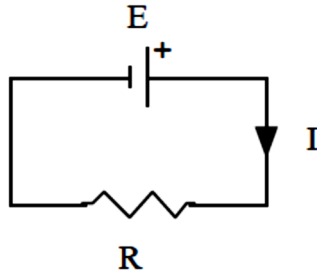
When making a measurement with any electrical meter, one must give careful consideration to the following factors:

- 1) **Function** -- Is the meter to be used to measure voltage, current, or resistance?
- 2) **Range** -- The term “range” refers to the range of values that can be measured by the instrument. For example, a voltmeter set on a 10 volt range can measure voltages between zero and 10 volts. The range setting of a meter thus indicates the **maximum value** that can be measured using that setting. Most meters have several ranges of operation. If you are not sure which range to use, start with the highest one. Then reduce the instrument setting to the lowest possible range which still contains the value you wish to measure -- this is the **optimum** or best range setting for that particular measurement and will give the most precise measurement possible. (The term “precision” refers to the number of significant figures in the measurement.)
- 3) **Polarity** -- Current and voltage measurements are directional -- i.e., both positive and negative values are possible. Voltmeters must be connected so that the + terminal of the meter is connected to the high potential side of the element being measured. Ammeters must be connected so that current flows into the + terminal of the meter.
- 4) **Placement** -- Meters must be properly placed in a circuit to make each type of measurement. Proper meter polarity and placement will be illustrated after a brief discussion of circuit diagrams.

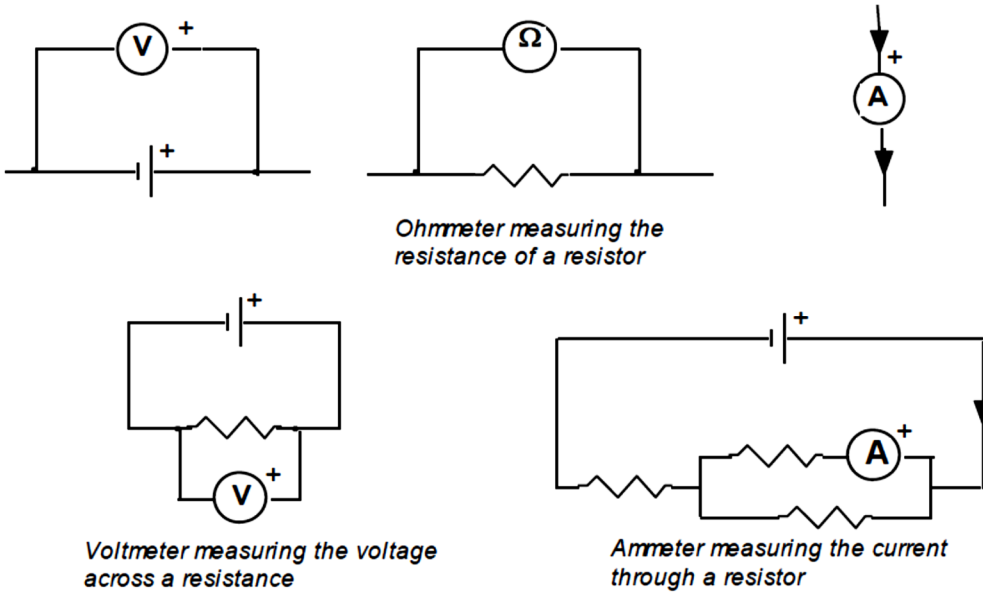
Circuit diagrams are figures or drawings that depict particular electrical circuits. You will need to become familiar with circuit diagrams and be able to construct a circuit using the diagram as a guide. The following symbols are used to represent electrical quantities:



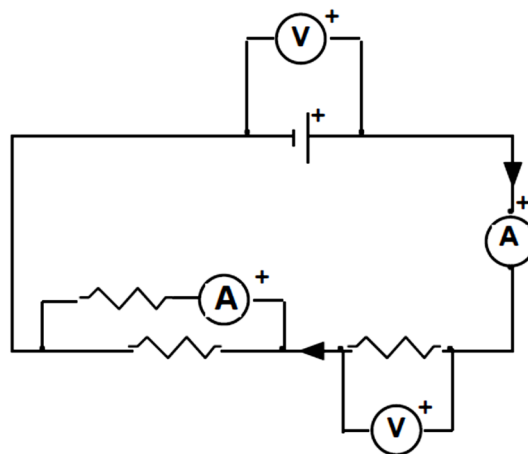
The electrical devices that we will examine in this exercise can be characterized entirely by their resistance. Thus, we often speak of an electrical device as “a resistance”. Lines joining voltage sources and resistances represent connecting wires. The circuit diagram below shows a resistance of  $R$  ohms connected to a voltage source of strength  $E$  volts with a current of  $I$  amps flowing in the circuit.



The following diagrams show the proper polarity and placement of each type of electrical meter (note the symbols used to represent each type of meter):



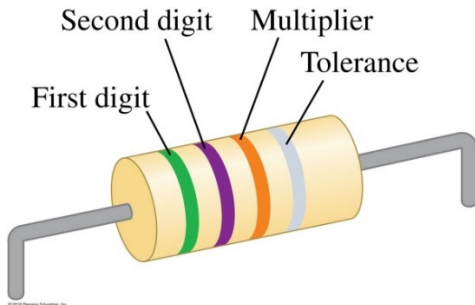
The following diagram shows an electrical circuit with meters properly positioned to make several different measurements:



**Carbon resistors**

**Resistor Color Code**

Band Colour	Significant Digit	Mutiplier	Tolerance
Black	0	1	
Brown	1	10	
Red	2	100	
Orange	3	1k	
Yellow	4	10k	
Green	5	100k	
Blue	6	1M	
Violet	7	10M	
Gray	8	-	
White	9	-	
Gold	-	0.1	5%
Silver	-	0.01	10%
No Band	-	-	20%



Example



**Procedure**

[**Important notes:** 1) Check with your instructor if you are not sure that a circuit is properly connected. 2) When using an electrical meter to measure an unknown electromagnetic quantity, start your measurement with the meter at its highest range setting, and lower the setting until you obtain the **optimum range**.

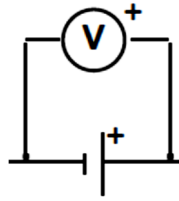
Using the diagram on page 4, familiarize yourself with the operation of the Digital Multimeter (DMM).

**I. Voltage measurements**

**a) Measuring the strength of a voltage source**

The strength of a voltage source is defined as the voltage difference between its (pos) + and (neg) – terminals when no current is flowing through it. When a voltmeter is used to measure the strength of a voltage source, it will draw a small current and the resulting measurement will be only approximate. The approximation, however, will be a very good one.

**i) Wet cell**



Construct a **wet cell** as shown in the figure above. It may smell unpleasantly. In such cases you may dilute the sulfuric acid. Measure its strength (voltage) using both the digital voltmeter (DMM) and the analog voltmeter. Connect the alligator clips directly to the metal plates. To get some practice in using different range settings, **use as many different ranges as possible on both instruments**. Record the measurements for **each** range. (CAUTION: Don't leave the analog voltmeter connected to the wet cell for more than a few seconds. It has a nasty tendency to drain the wet cell's energy.)

Which metal is the + terminal of the cell?

Which DMM range gives the most precise measurement (i.e. which range gives the measurement with the most significant figures)?

Which analog voltmeter range gives the most precise measurement?

## ii) Dry cell

Repeat part i) for a **dry cell**. Which terminal is positive?

For each meter, which range gives the most precise measurement?

**iii) A power supply** is a usually variable source of voltage. Its circuit symbol is shown below. (The arrow indicates that the strength of the voltage source is variable.)



Many power supplies have built-in voltmeters. In most cases, these meters are not very accurate and should not be used to measure the output voltage of the supply. You will now examine the accuracy of the meter of the laboratory power supply.

Connect the DMM to the power supply's output terminals. Use the DMM, **at its optimum range setting**, to set the power supply to 1.0 volt. Now read the built-in voltmeter and record its

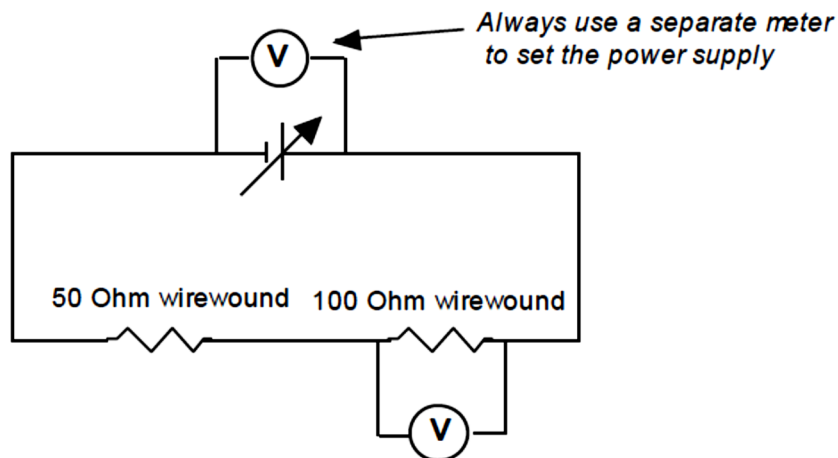


reading. (The built-in meter reading will normally be different than the DMM reading.) Repeat for power supply settings of 2.4, 5.0, 7.5, 10.0, 13.2, 15.0, 20.0, and 24.0 volts.

In any measurements we make in this laboratory, we will always assume that the DMM is the most accurate meter available. Compare the DMM readings with the readings of the power supply's built-in meter. Based on your comparison, answer the following question: **When using the power supply, why should you always use a separate voltmeter to measure its voltage?**

### b) Measuring the voltage across a resistance

Construct the circuit shown below with the power supply at its zero setting. Then use a DMM to set the power supply to 1.00 volt.



1) Measure the voltage across the 100 Ohm resistor using another DMM on its **optimum range setting**. Record this voltage. Repeat for power supply settings of 2.00, 3.00, 4.00 and 5.00 volts. What numerical relationship exists between the voltage across the 100  $\Omega$  resistor and the voltage of the power supply? (Try looking at the ratio of the two. Does this ratio remain constant?)

2) (Optional) Repeat step 1 using the analog voltmeter.

3) Repeat step 1 using computer voltage probe

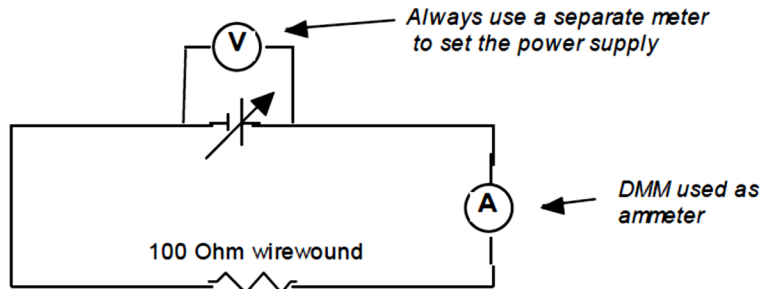
Which method gives the best results?

## II. Current Measurements

Analog ammeters are very sensitive instruments (voltmeters are rugged by comparison). An analog ammeter can be destroyed if more current than it is designed to measure is allowed to flow through it. (A DMM used as an ammeter will usually have a fuse which protects the meter in case of overload.) **Please be careful when using any ammeter!** To avoid excessive currents, follow these two rules: (1) Always start with the power supply set at zero and increase it slowly while

carefully watching the ammeter reading; (2) Start with the highest ammeter range setting possible and go to lower ranges only when you are sure the current is less than the maximum for that setting.

Construct the following circuit with the power supply set at zero.



**Have your instructor check your circuit before you continue.**

(1) **Using 0- 2, 0-20, 0-200 range settings** for the DMM (make sure it is set to function as an ammeter), measure the current in the circuit for power supply settings of 1.0, 2.0, 3.0, 4.0, and 5.0 volts. **Record the measurement on each range. Make one column for Voltage, three columns for Current with each range and three columns for Resistance ( $R=V/I$ ). Compare resistance value with the given value.**

(You will notice that for a given voltage setting the current measurement will change as you change the ammeter range. This is due to the internal resistance of the ammeter, which is typically larger for a higher range of current. Don't worry about it.)

(2) (Optional) Repeat part (1) using the analog ammeter. (Start with the highest range setting -- 100 mA. Don't go to a lower range setting unless you're sure that the current is within that lower range.)

(3) (Optional) Repeat part (1) using computer current probe.

### **Carbon resistor – 1000 $\Omega$**

Complete the circuit using 1000  $\Omega$  carbon resistor placed on breadboard using the circuit shown above for 100 ohm resistor. Connect the voltage probe and current probe to the computer.

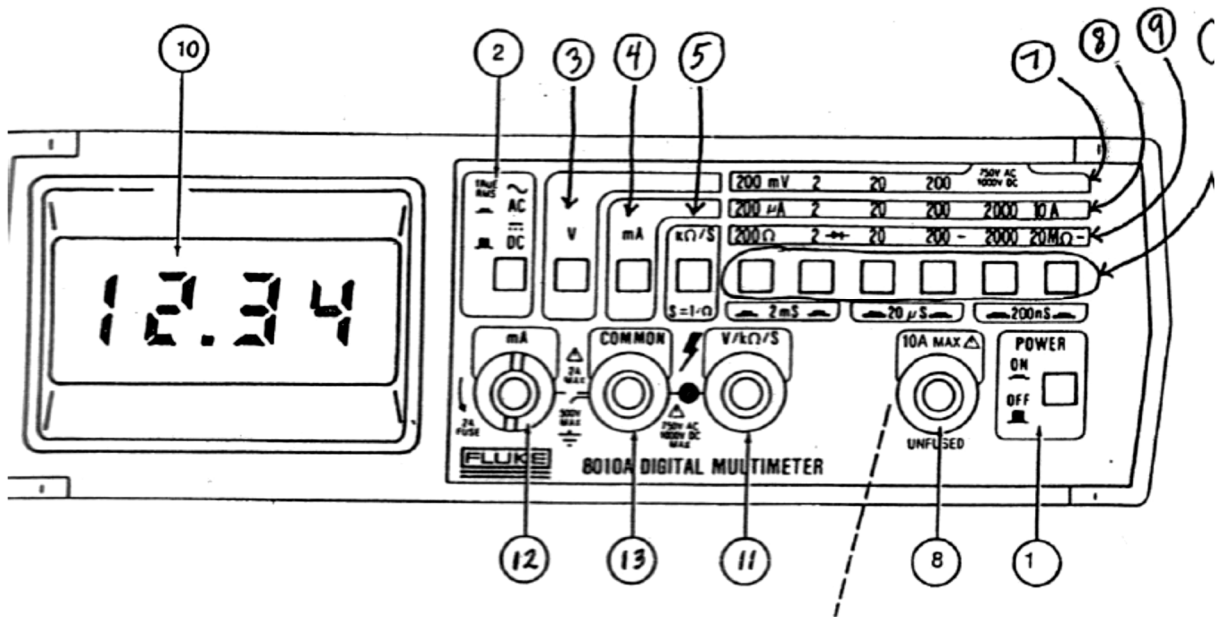
(a) Find voltage and current across the 1000  $\Omega$  resistor using computer voltage probe and computer current probe for the power supply voltages 1 V to 5 V in steps of 1V. Note that the current probe may require 7 mA minimum current.

(b) Calculate resistance and compare with the given value.

Meter	Range	Smallest Scale Division	Read meter to
Voltmeter	150 V.	5 V.	1 V.
	15 V.	0.5 V.	0.1 V.
	1.5 V.	0.05 V.	0.01 V.
Ammeter	500 mA.	10 mA.	1 mA.
	100 mA.	2 mA.	0.2 mA.
	10 mA.	0.2 mA.	0.02 mA.

Unit	Abbreviation	Size
Volt	V.	---
Millivolt	mV.	.001 V.
Amp	A.	---
Milliamp	mA.	.001 A.
Microamp	$\mu$ A.	.000001 A.

**DIGITAL MULTIMETER**



**General Controls**

- 1 Power Switch -- turns DMM on and off
- 2 AC/DC select switch -- sets DMM to measure either direct or alternating current quantities

**Function Selection**

3 Voltage select switch -- sets DMM to act as a voltmeter

4 Current select switch -- sets DMM to act as an ammeter

5 Resistance select switch -- sets DMM to act as an ohmmeter

**Range Selection**

6 Range selection switches -- select the range of the measurement

7 Voltage range labels -- indicate range of DMM as voltmeter

8 Current range labels -- indicate range of DMM as ammeter

9 Resistance range labels -- indicate range of DMM as ohmmeter

**Display**

10 LCD digital display -- the instrument reading appears here as a decimal number. Use the function and range selected to determine the units of the measurement.

**Overrange indication:** If the value of the quantity being measured is too large for the range you have selected, the DMM will display the value “1.” or “1”.

**Terminals**

11 + voltage terminal, resistance terminal

12 + current terminal

13 – current terminal, – voltage terminal, resistance terminal

**To measure voltage:** use terminals 11 and 13

**To measure current:** use terminals 12 and 13

**To measure resistance:** use terminals 11 and 13

## Lab 6: DC Circuits II

### Equipment:

1. Low voltage DC/AC power supply
2. Wire wound resistors 10  $\Omega$ , 100  $\Omega$
3. 2 DMMs (one orange and one grey)
4. New voltage probe
5. New current probe
6. Logger pro
7. A small 5 volt bulb
8. Barrel diode
9. Connecting wires, alligator clips

### Introduction

This laboratory exercise focuses on resistance. You will use two different methods to measure the resistance of circuit elements. The resistance of any electrical element is defined as the voltage across the element divided by the current flowing through it:

$$R = V/I$$

The unit of resistance is the ohm ( $\Omega$ ). You will often see the abbreviations  $k\Omega$  and  $M\Omega$  -- these stand for kilo-ohm (one thousand ohms) and mega-ohm (one million ohms).

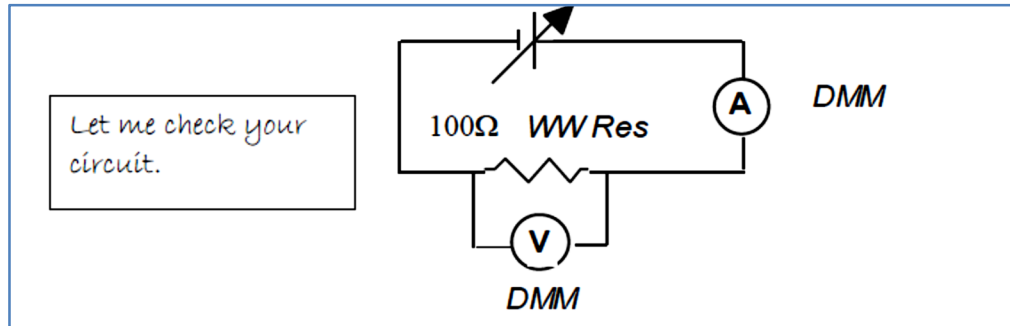
### Measurement of resistance

In order to measure the resistance of an electrical element, we arrange to have current flowing through the element and carefully measure the magnitude of the current as well as the voltage (potential difference) across the element. Dividing the voltage by the current gives the resistance of the element **for that particular current**. If we make the same measurement for a different current, the resistance for the new current may be the same as the previously measured resistance or it may be different. Circuit elements whose resistance does not change with current are called **ohmic resistors**.

In order to see clearly how the resistance of an element depends on the current, we construct a voltage versus current graph (V-I graph) for the element. The resistance of the element at any point on the graph can be found by dividing the voltage at that point by the corresponding current. If the V-I graph for an element is a straight line, the element is an ohmic resistor and the slope of the graph is equal to the resistance of the element. If the graph is not a straight line, the element has a non-ohmic resistance and the slope does not have any simple relationship to the resistance.

### Measurement of resistance using the voltmeter-ammeter method

We shall use this method to examine the resistance of the  $100\ \Omega$  wirewound resistor. Construct the circuit shown below.



To construct the V-I graph for the  $100\ \Omega$  resistor, the power supply will be set to a number of different values and the voltage across the element and the current through it will be measured for each setting. The voltage and current data will then be plotted on a V-I graph.

Start with the power supply set to zero (you may need to disconnect the power supply from the circuit to obtain zero voltage). The voltage and current will both be zero and you should record these values in your laboratory notebook. Then set the power supply so that the voltmeter across the resistor reads 0.5 volts. Read the current value given by the ammeter. Repeat for voltages of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 volts.

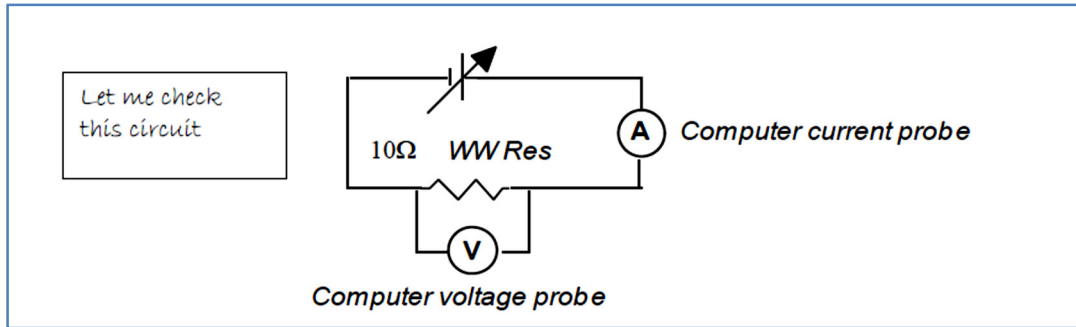
Use the **Excel** to plot V (on the vertical axis) versus I (on the horizontal axis). [Don't forget to put proper axis labels and axis units on your graph.] The data points should lie on a straight line (if they don't, you may have done something wrong!). This straight-line V-I graph shows that the  $100\ \Omega$  wire-wound resistor is an ohmic resistor -- its resistance is the same for all currents. Use the curve fitting capabilities of Excel to determine the slope of the best fit straight line. This slope will be equal to the resistance of the resistor in ohms if you entered your current data in units of amps. If you entered your current data in units of milliamps, you must multiply the slope by 1000 to obtain the resistance in ohms. Give your graph a title. Use a title such as "V-I graph for  $100.0\ \Omega$  resistor". **Print out a copy of your graph-1.**

### Measurement of resistance using the computer method

The computer can be used to collect voltage and current data and plot it as a V-I graph. As you are making these measurements, think about the advantages and disadvantages of the computer measurements compared to the measurements made using the voltmeter-ammeter method.

Construct the following circuit.

### 10 $\Omega$ Ohmic resistor



- Remove one of the two graphs in your program, and use the command “page” and “Auto Arrange” feature to make that graph fill up your screen. Change the vertical axis variable to Potential (with axis limits of -5 to +5 volts) and the horizontal axis variable to Current (with axis limits of -0.200 A to +0.200 A) by left clicking on each axis label.
- Finally, go to the Data Collection panel (with the stopwatch icon) and change the length to 120 seconds and your data collection rate to 15 samples per second.. The computer is now ready to automatically make a V-I graph for the 10.0 Ω wirewound resistor (PLEASE NOTE THAT THESE RESISTORS CANNOT TAKE MORE THAN 0.2 AMPS OF CURRENT, AND WILL BURN WITH MORE).
- THE FOLLOWING STEP 1 AND STEP 2 MEASUREMENTS SHOULD BE DONE IN 120 SECONDS
- STEP 1: With the power supply set to zero, press the COLLECT button. Slowly increase the power supply setting until the voltage reaches **+2 volts**, and then decrease it slowly to zero. Repeat this couple of times. The graph you see should be a straight line in the first quadrant. (It won't be perfect because of the jitter present in both the voltage and current measurements.)
- STEP 2: Now set the power supply to zero and reverse the power supply connections -- this will cause both the current and voltage across the resistor to become negative. Slowly turn the voltage down to -2 volts and back to zero. Repeat couple of times. You should see a continuation of the straight line in the third quadrant.
- Then choose the “Linear Fit” button on the second row of menu items. A best fit straight line will appear on the graph along with a function of the form

$$y = b_0 + b_1x$$

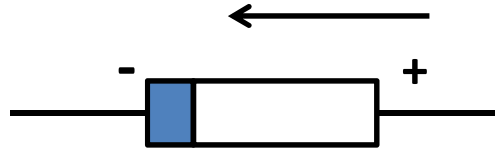
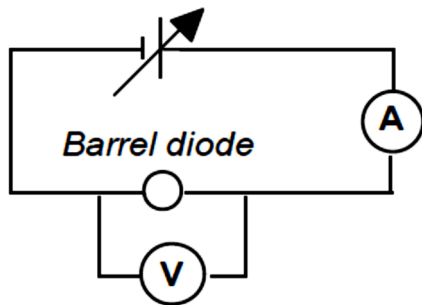
The resistance of the 10.0 Ω resistor is equal to  $b_1$ -- this number should be close to 10.

- Double-click on the graph and select the “Graph Options” tab. Give your graph a title. Use a title such as “V-I graph for 10.0 Ω resistor”. From the **FILE** menu, select **Page Setup** and set the graph for *Landscape* orientation. Select **Print Graph** from the **FILE** menu and **print the graph-2**.
- Repeat the above for the two elements (barrel diode and mini lamp) listed below. Since neither of these elements is an ohmic resistor, you won't need to make a linear fit for these graphs. Be sure to use both positive and negative voltages and currents. **Don't forget to**

**print the graphs-3 and graph-4** for these elements. Explain briefly in your lab report why these elements behave the way they do, and how their behavior might be useful.

### Barrel diode – Non-ohmic resistor

- Connect the diode in the circuit as shown in the figure below. To keep from burning the diode out, don't let the current exceed **500 mA**. You must be alert to the fact that when the voltage is applied to the diode in one direction, the current takes a sudden jump from zero to several hundred milliamps. If you are not careful, the 500 mA limit can be exceeded. Take care that your voltage do not increase beyond **0.9 V**. To obtain a good graph, make sure that when you are increasing or decreasing the power supply setting you do it very slowly. The whole measurement should be done in 120 seconds.



### Mini lamp – Non-ohmic resistor

- Change the horizontal axis scale to ( $-200 \text{ mA} \rightarrow 200 \text{ mA}$ ). Don't let the voltage exceed **5 volts**. The lamp burns out easily. To obtain a good graph, make sure that when you are increasing or decreasing the power supply setting you do it very slowly. The whole measurement should be done in 120 seconds.



## Lab 7: DC Circuits III

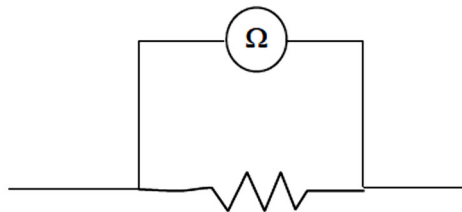
### Equipment:

1. Low voltage DC/AC power supply
2. Wire wound resistors  $10\ \Omega$ ,  $15\ \Omega$ ,  $25\ \Omega$
3. 1 DMM (Orange)
4. Very thin copper wire (1 m in length)
5. Screw gauge (micrometer)
6. New voltage probe
7. New current probe
8. Logger pro
9. LCR meter
10. Three  $47\ \mu\text{f}$  capacitors
11.  $100\ \text{k}\Omega$  resistor
12. Bread board
13. Connecting wires, alligator clips

### I. Resistance measurements with an ohmmeter

An ohmmeter measures the resistance of a circuit element by internally applying a small known voltage to the element and then measuring the current that flows through it. The ohmmeter then calculates the resistance by dividing the voltage by the current. The resistance value is then displayed on the meter readout. Thus, an ohmmeter measures only one point of the V-I graph of an element and, unless the device is ohmic, we know the value of the resistance only at that point. For this reason, ohmmeters are normally used only to measure resistances of elements that are ohmic.

As shown in the figure below, the ohmmeter should be connected directly to the device whose resistance you are measuring -- no voltage sources or other elements should be in the circuit!



Be careful in reading resistance values. If for example, the DMM is set on the  $20\ \text{k}\Omega$  range and it displays the number 5.36, the value of the resistance is **not**  $5.36\ \Omega$  but rather  $5.36\ \text{k}\Omega = 5,360\ \Omega$ .

- Use the DMM set to function as an ohmmeter to measure the resistance of  $R_1$ ,  $R_2$  and  $R_3$  and record your values.
- For each of the following combinations of resistors, predict what the equivalent resistance of the combination will be. Then use the ohmmeter to measure the equivalent resistance. Explain any differences between your prediction and the measured value.

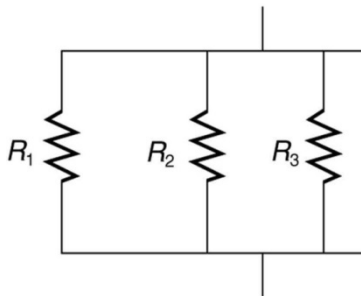
i)  $R_1$ ,  $R_2$ , and  $R_3$  connected in series



Predicted value:

Measured value:

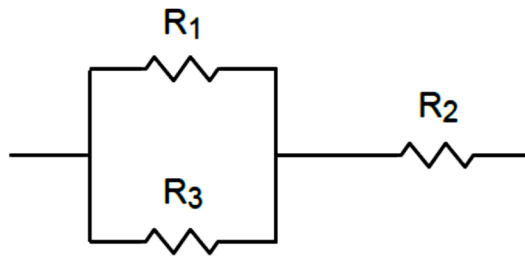
ii)  $R_1$ ,  $R_2$ , and  $R_3$  connected in parallel



Predicted value:

Measured value:

iii)  $R_1$ ,  $R_2$ , and  $R_3$  connected in the series/parallel combination shown in the following figure



Predicted value:

Measured value:

## II. Resistivity

The resistance of a piece of wire is given by

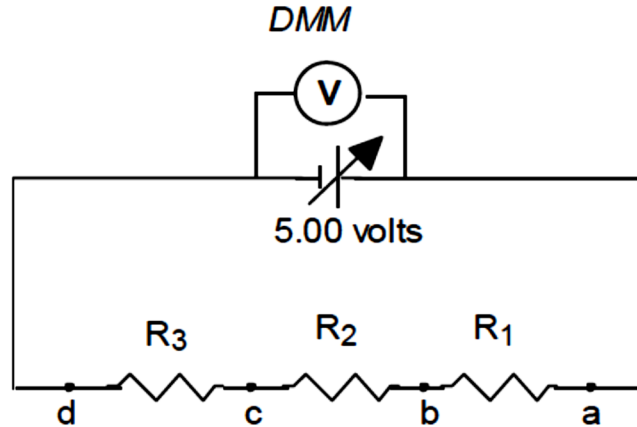
$$R = \frac{\rho L}{A},$$

where  $\rho$  is the resistivity of the material of which the wire is constructed,  $L$  is the length of the wire between the connection points (the wire was cut to be 1.0 m in length), and  $A$  is the cross-sectional area. Make appropriate measurements and determine the value of the resistivity of the wire on your table. Use the LCR meter to measure the resistance of the wire provided. (You will probably need to use a screw gauge to measure the diameter of the wire. Information on the use of a screw gauge is provided at the end of this laboratory exercise.) **Show your instructor the  $\rho$  value you calculate, and compare to the accepted value of  $\rho$  ( $1.68 \times 10^{-8} \Omega \cdot \text{m}$ ) for copper.** Please note: 1) The screw gauge we currently have has a scale of 0.001"/div. 2) Measure the resistance of the bare wire, with no posts or cables. 3) Measure the diameter of the bare wire, with no coatings.

## III. Resistances in Series

In this section, you will examine the current and voltage relationships of resistors connected in series. Remember that for resistors in series, currents are equal and voltages add. When resistors are connected in series, the current flowing through each resistor is the same and the voltages across each resistor add up to give the total voltage across all of the resistors.

Construct the following circuit and set the power supply to 5.00 volts. After every change you make in this circuit, check to make sure that the power supply voltage is still at 5.00 volts.



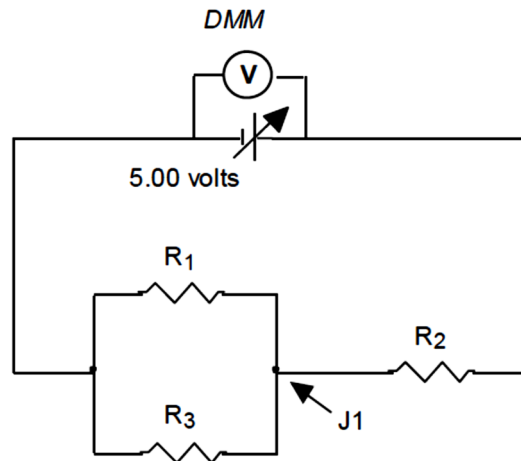
Use voltage probe to measure the voltages across each resistor -- i.e., measure  $V_{ab}$  (this is  $V_1$  - the voltage across resistor 1),  $V_{bc}$  ( $V_2$ ), and  $V_{cd}$  ( $V_3$ ). Do these three voltages add up to 5.00 volts (i.e., does  $V_1 + V_2 + V_3 = 5.00$ )?

Now use current probe to measure the current through each resistor. To do this, you will have to open the circuit and insert the ammeter probes at points a, b, and then c. The current at point a will be  $I_1$  (the current through  $R_1$ ), the current at point b will be  $I_2$ , and the current at c will be  $I_3$ . Are all of the currents the same (i.e., does  $I_1 = I_2 = I_3$ )?

You may find some small discrepancies in your results -- the voltages may not add up to exactly 5.00 volts or the currents may not be exactly equal to each other -- these are due to the fact that the probes have some internal resistance which can produce small alterations in circuit behavior. These discrepancies, however, should be **very** small.

#### IV. Kirchhoff's laws

In this part, you will see if Kirchhoff's Laws are obeyed by the currents and voltages in a series/parallel circuit. Construct the circuit shown and set the power supply to 5.00 volts. After every change you make in this circuit, check to make sure that the power supply voltage is still at 5.00 volts.



Measure the current through each resistor and the voltage across each resistor.

a) **Kirchhoff's Current Law** --- Does KCL hold at junction J1? (i.e., does  $I_2 = I_1 + I_3$ ?)

b) **Kirchhoff's Voltage Law**

Does KVL hold for the closed loop consisting of R2, R1, and the Power Supply? Does KVL hold for the closed loop consisting of R3 and R1?

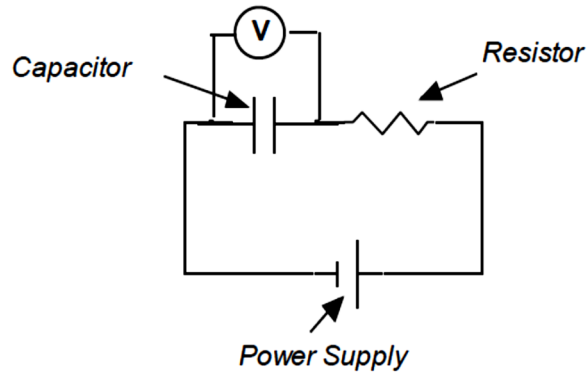
## V. RC Circuits

### (a) Charging a Capacitor:

When an uncharged capacitor is connected to a source of voltage, charge will flow from the source to the capacitor until the voltage of the capacitor reaches that of the source. This charging process does not occur instantaneously, but at a rate which is controlled by the amount of resistance in the circuit. The higher the resistance is, the slower the rate of charging. In addition, the rate at which charge flows onto the capacitor decreases with time -- the flow of charge is rapid at first but it decreases gradually and becomes almost zero as the capacitor voltage approaches that of the voltage source. This behavior is expressed by the equation for the voltage across a charging capacitor as a function of time:

$$V(t) = V_0 \left( 1 - e^{-\frac{t}{RC}} \right)$$

Where  $V_0$  is the voltage of the power supply,  $R$  is the resistance in the circuit, and  $C$  is the capacitance (so that  $\tau = RC$  is the charging time constant)

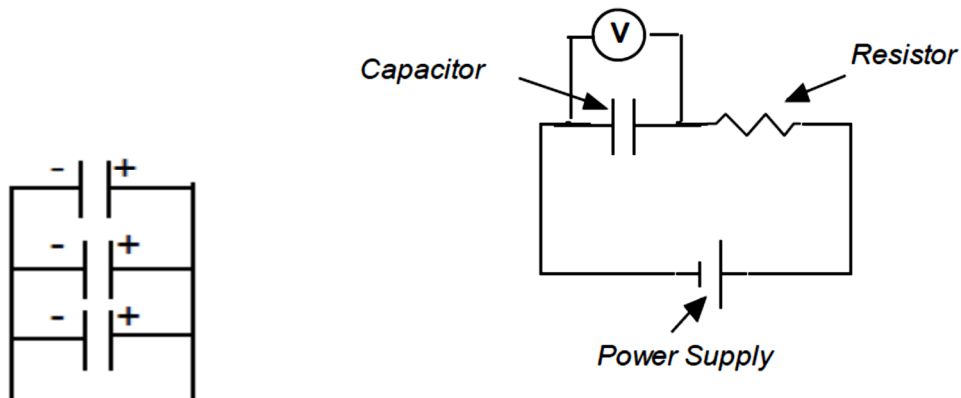


Use the breadboard to connect a  $47\ \mu\text{F}$  capacitor in series with a  $100,000\ \Omega$  resistor. Use the Vernier voltage probe so that you can obtain a graph of the voltage vs. time across the capacitor (the black wire to the negative side). Discharge the capacitor by shorting it out. Now, connect a wire from the negative side of the power supply to the negative side of the capacitor. Start collecting data with your voltage probe, then connect a wire from the positive side of the power supply (which should still be set at 3.00 volts) to the free end of the resistor. The capacitor should charge in just a few seconds. Now, fit the curve you have obtained for the voltage across the capacitor with the expression that most closely matches the theoretically predicted equation. What is your experimentally determined time constant,  $\tau$ ? Report your percentage error for the time constant, using the theoretically predicted value as your accepted value. **Print out the graph-1.**

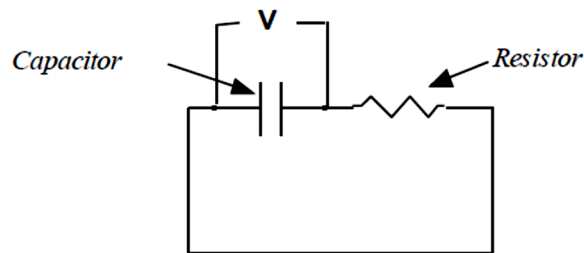
Notice what the final voltage across the capacitor is as recorded by your computer voltage probe. Discuss in your report why that voltage is less than the voltage coming from your power supply.

### (b) Discharging a Capacitor

If a charged capacitor is disconnected from the charging source, it will (in the ideal case) maintain its charge forever. If the two terminals of the capacitor are connected together by a conducting pathway, all of the positive charge from one plate will eventually flow to the negative plate and the capacitor will become uncharged. The rate at which this discharging process occurs depends upon the amount of resistance in the circuit -- the more resistance, the slower the rate of discharge. The rate of discharge decreases as the charge on the capacitor (and the voltage across the capacitor) is reduced, and becomes zero when the capacitor is completely discharged.



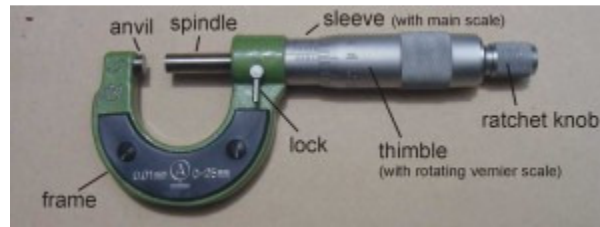
Use the circuit above with three  $47\ \mu\text{F}$  capacitors connected in parallel and a  $100\ \text{k}\Omega$  resistor. Use the Vernier Voltage Probe to measure the voltage across the capacitor (the black wire to the low voltage side). Set the power supply voltage to  $3.0\text{V}$  and charge the capacitor up to the power supply voltage (it should reach at least  $2.95\ \text{V}$ ). Then, after hitting Collect in Logger Pro so that you will have a record of the voltage vs. time, disconnect the wires that are connected to the power supply and connect them directly together. The circuit should now look like the figure below.



Look at the  $V$  versus  $T$  data for the discharging capacitor displayed in Logger Pro. Use Curve Fitting to determine the Best Fit Function (select only the portion of the curve recorded while the capacitor was discharging). Does your graph indicate that the magnitude of the rate of change of the voltage decreases with time? How long did it take for the voltage to decrease to  $1/3$  of its initial value? This time interval is called the characteristic time,  $\tau$ , and it should be equal to the value of the resistance multiplied by the value of the capacitance. That is,  $\tau = RC$ . **Print out the graph-2.**

Now, repeat the above experiment with just a single  $47\ \mu\text{F}$  capacitor. What would you predict will happen to the discharge time in this case? Run the experiment. Does the discharge time behave like you expected? Why or why not?

## Screw Gauge - Micrometer



A quick guide on how to read a micrometer screw gauge. Similar to the way a vernier caliper is read, a micrometer reading contains two parts:

- the first part is contributed by the main scale on the sleeve
- the second part is contributed by the rotating vernier scale on the thimble



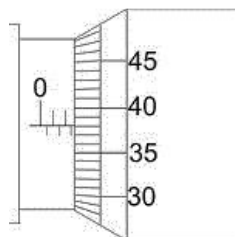
A typical micrometer screw gauge

The above image shows a typical micrometer screw gauge and how to read it. Steps:

- To obtain the first part of the measurement: Look at the image above, you will see a number 5 to the immediate left of the thimble. This means 5.0 mm. Notice that there is an extra line below the datum line, this represents an additional 0.5 mm. So the first part of the measurement is  $5.0+0.5=5.5$  mm.
- To obtain the second part of the measurement: Look at the image above, the number 28 on the rotating vernier scale coincides with the datum line on the sleeve. Hence, 0.28 mm is the second part of the measurement.

You just have to add the first part and second part of the measurement to obtain the micrometer reading:  $5.5+0.28=5.78$ mm.

To ensure that you understand the steps above, here's one more example:



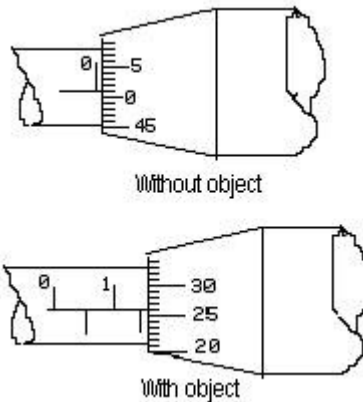


First part of the measurement: 2.5 mm

Second part of the measurement: 0.38 mm

Final measurement: 2.88 mm

Now, we shall try with zero error. If you are not familiar on how to handle zero error for micrometer screw gauge, I suggest that you read up on Measurement of Length.



The reading on the bottom is the measurement obtained and the reading at the top is the zero error. Find the actual measurement. (Meaning: get rid of the zero error in the measurement or take into account the zero error)

Measurement with zero error: 1.76 mm

Zero error: + 0.01 mm (positive because the zero marking on the thimble is below the datum line)

Measurement without zero error:  $1.76 - (+0.01) = 1.75$  mm.

## Lab 8: Motion of Charged Objects in Magnetic and Electric Fields

In this laboratory exercise, we will use Interactive Physics to examine the motion of charged particles in several different electric and magnetic field configurations.

Open the Interactive Physics program. In the **VIEW** menu select Workspace. Turn on Rulers, Grid Lines, XY Axes, and Coordinates. The solid lines you see are the X and Y axes -- the Y axis is vertical and the X axis is horizontal. The X and Y coordinates of the mouse pointer are given in meters at the bottom of the screen. This can be helpful in determining the position of various points on the path of a charged object. If the origin of the XY system is not in the center of the screen use the Scroll Bars to move it there. Go to the **WORLD** menu and turn gravity off.

### I. Uniform Magnetic Field

In this part of the laboratory exercise, we will create a uniform magnetic field of magnitude 2.00 T **directed into the screen**. It will point in the **negative Z** direction. (The XYZ coordinate system is a right-handed system -- if the thumb of your right-hand points in the X direction and the fingers in the Y direction, your palm will face in the positive Z direction.) Since the magnetic force on a moving charge is given by

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

the components of F will be given by

$$F_x = -qv_y B$$

$$F_y = +qv_x B$$

This force field can be created by going to the **WORLD** menu and opening the Force Field window. Click the Field radio button and set the Sample Force box to Custom.

Enter the following equations in the force component boxes:

$$F_x: -\text{self.charge} * \text{self.v.y} * 2$$

$$F_y: \text{self.charge} * \text{self.v.x} * 2$$

The quantity “self.charge” is Interactive Physics’ way of representing the charge q; the term “self.v.y” is the y component of the object’s velocity vector and “self.v.x” is the x component of the object’s velocity vector. The “2” stands for 2 Tesla -- the magnitude of the magnetic field vector.

a) Click OK to return to the Interactive Physics window. Use the drawing tools to create a small circular object. Keep the object size as small as possible. Use Window → Properties for the object to specify the following object parameters:

$$\begin{aligned} X &= 0 \text{ m.} \\ Y &= 0 \text{ m.} \\ V_x &= 10 \text{ m/s.} \\ V_y &= 0 \text{ m/s} \\ m &= 1 \times 10^{-5} \text{ kg. (Enter as 0.00001)} \\ q &= +1 \times 10^{-4} \text{ C. (Enter as 0.0001)} \end{aligned}$$

Note that the object will start at the origin with a velocity of 10 m/s in the +X direction. Keep the origin at the middle of the screen and zoom the screen.

**Predict** the size of the circular orbit the object will follow using:

$$R = \frac{mv}{qB}$$

**Predict** the period of the circular motion using:

$$\begin{aligned} v &= R\omega \\ \omega &= \frac{v}{R} = \frac{qB}{m} \\ \omega &= 2\pi f = \frac{2\pi}{T} = \frac{qB}{m} \\ T &= \frac{2\pi m}{qB} \end{aligned}$$

**Predict** the direction of the circular motion (clockwise or counterclockwise) using the right-hand rule.

Create time, position and velocity meters by clicking **measure** → **time** → **Position (X)** (Expand this) → **velocity (All)**. Click **Define** → **Vectors** → **Velocity** to choose the magnitude of the object's velocity vector. Turn **TRACKING (Window** → **Appearance** → **Track outline**) on to Every Frame. Use World → Accuracy ~0.001s.

Run the simulation. Is the path of the object a circle? What is the path's radius? (Measure from the screen.) What is the period of the motion? (Measure from the position graph.) Does the velocity magnitude remain constant throughout the motion? (Check on the screen.) Does the object move in the CW or CCW direction? If any of your predictions are incorrect, find out the reason.

Note that we are using the **Predict, Observe, Resolve cycle** that we used in laboratory exercise #1. In this laboratory exercise, you should write your Predictions (with reasons), Observations, and Resolutions in your **laboratory notebook**.

**Before you change the properties of the object, right click of the object and click exit. (Tracking will disappear and object will come to original position)**

b) [ $q = +1 \times 10^{-4}$  C,  $m = 2 \times 10^{-5}$  kg,  $V_x = 10$  m/s,  $B = 2.00$  T.]

Change the object parameters to match those listed above. Predict the R and T values for the object's motion as well as the direction of motion and then run the simulation. Compare prediction with observation and resolve any differences.

c) [ $q = +2 \times 10^{-4}$  C,  $m = 1 \times 10^{-5}$  kg,  $V_x = 10$  m/s,  $B = 2.00$  T.]

Predict, observe, resolve.

d) [ $q = -1 \times 10^{-4}$  C,  $m = 1 \times 10^{-5}$  kg,  $V_x = 10$  m/s,  $B = 2.00$  T.]

Predict, observe, resolve.

e) [ $q = +1 \times 10^{-4}$  C,  $m = 1 \times 10^{-5}$  kg,  $V_x = 10$  m/s,  $B = 1.00$  T.]

Note that we are changing B to 1 Tesla. (You will have to go to the Force Field window to do this.) Predict, observe, resolve.

f) [ $q = +1 \times 10^{-4}$  C,  $m = 1 \times 10^{-5}$  kg,  $V_x = 20$  m/s,  $B = 2.00$  T.]

Change the initial velocity in the x-direction to 20 m/s and return B to 2.00 T. Predict. observe, resolve.

## II. Velocity Selector

The velocity selector will consist of a uniform magnetic field of 2.00 T directed into the screen and a uniform electric field of magnitude 10 V/m **in the negative Y direction**. To create this combination of fields, go to the Force Field window and change the magnetic field magnitude back to 2.00 T. Add to the  $F_y$  equation the term

$$-\text{self.charge} * 10$$

This is simply the Y component of the electric force.

Use the same X, Y, m, and q values used in part Ia. Select a velocity vector that will enable the object to pass through the velocity selector without experiencing any change in its velocity (either magnitude or direction) -- i.e., the object will move in a straight line at constant speed. **Let the instructor see this simulation when you have it working!**

Try the simulation again with a negative charge. Try different values of the mass and charge. Does the same velocity work for all of these cases?

What happens if you use the negative of the velocity used above? Observe the path carefully.

### III. Linear Accelerator

The simplest type of particle accelerator consists of a uniform electric field that is confined to a certain region of space. A charged particle is accelerated while in the field and when it leaves the field it moves with constant velocity.

Go to the Force Field window and enter the following:

$$F_x: \text{if}(\text{and}(\text{self.p.x} \geq 0, \text{self.p.x} \leq 1), \text{self.charge} * 200, 0)$$

$$F_y: 0$$

The equation for  $F_x$  is in the form of an Interactive Physics “if” function. Such a function has the following general form: **if(A, B,C)** -- If the condition represented by A is true, then the function has the value B; if the condition represented by A is false, then the function has the value C. The condition A in our equation for  $F_x$  is given by an Interactive Physics “and” function which takes the following general form: **and(D, E)** -- If conditions D and E are both true, the *and* function is true; if either D or E is false, then the *and* function is false.

The term “self.p.x” stands for the x component of the position of the charged object --i.e., its X coordinate. Thus the *and* function will be true if  $0 \leq X \leq 1$  (i.e., if the X coordinate of the object is between 0 and 1). When the object is between 0 and 1 the *if* function has the value “self.charge\*200” which is just  $q \cdot E$ . (The magnitude of the electric field is 200 V/m.) If the object is outside of the region between 0 and 1, the *if* function gives the value 0.

We have constructed an electric field that has a magnitude of 200 V/m in the +X direction in the region from  $0 \leq X \leq 1$  and that is zero outside that region.

Use the properties window to make the object start at rest at the origin. Make its charge be  $1 \times 10^{-4}$  C. and its mass,  $1 \times 10^{-5}$  kg. Give initial velocity  $V_x$  as 10 m/s. Create a Velocity meter to measure the magnitude of the object’s velocity vector. Click **Define** → **Velocity** to choose the magnitude of the object’s velocity vector.

Before running the simulation, predict the velocity of the object when it leaves the linear accelerator. Remember a gain in kinetic energy ( $\frac{1}{2}mv^2$ ) equals a loss of the Potential energy (eV, Here  $V = 200$  V) when the force acting is conservative. Equate these two equations to get velocity  $v$ . Make sure you show your calculation in your lab write up! Also predict how the velocity will change when the object is outside the accelerator. Run the simulation. If your predictions differ from your observations, resolve the differences. You may need to change the accuracy setting by going to **WORLD**, selecting **ACCURACY** and then unselecting **AUTOMATIC** and choosing a shorter time step for the calculation. (0.001s, 0.01 m) (**Show the simulation to your instructor.**)

- Make the accelerator 2 meters long instead of 1 meter by writing new Fx with “x<=2”. Predict the final velocity and observe the simulation.
- Try increasing the electric field to 400 V/m and see what happens. (Leave the length of the accelerator at 2 meters.)

#### IV. Cyclotron

The cyclotron we will construct has a uniform magnetic field of 5.00 T pointing into the screen. It fills the entire Interactive Physics universe -- this would obviously be expensive to build, but we are not paying for it, so who cares. The electric field is zero everywhere except in a small gap that exists in the region  $-0.10 \leq X \leq +0.10$ . In this gap, the electric force has a zero Y component and an X component given by:

$$Q \cdot E \cdot \cos(2\pi f \cdot t)$$

where f is the cyclotron frequency ( $f = qB/2\pi m \rightarrow 2\pi f = qB/m$ ). The cosine function is used so that the electric field will always point in the direction in which the object is moving when it crosses the gap -- the object will always be given an energy boost by the electric field. We will use a charge of  $1 \times 10^{-4}$  C and an electric field of 1000 V/m -- the value of  $q \cdot E$  will thus be 0.1 N.

The Force Field will be the combination of the magnetic and electric fields shown below:

$$F_x: \text{if}(\text{and}(\text{self.p.x} \geq -0.1, \text{self.p.x} \leq +0.1), 0.1 \cdot \cos(2\pi f \cdot \text{time}), 0) - 5e-4 \cdot \text{self.v.y}$$

**Note:  $2\pi f$  must be calculated and entered as a number.**

$$F_y: 5e-4 \cdot \text{self.v.x}$$

The  $5e-4$  terms are the value of  $q \cdot B$ . You will have to determine the correct numerical value of the term  $2\pi f$  and enter that number in the equation for  $F_x$ . Use the properties window to set the mass of the object to  $1 \times 10^{-5}$  kg. Have the object start at rest at the origin.

Create a **kinetic energy meter** (you need only measure the translational KE) to monitor the object's KE and **velocity meter**. Run the simulation. You may have to zoom the screen out to get a better view of the object's path. You will probably also need to decrease the time step of your simulation, if you haven't already.

- What is the shape of the path (circle, spiral, helix, parabola, etc.)?
- How much kinetic energy does the object gain every time it crosses the gap? (Remember that the gain in kinetic energy equals the loss of the Potential energy when the force acting is conservative.) Use velocity value from the velocity meter to calculate final kinetic energy. Calculate potential energy eV. Calculate how many times it crosses the gap?
- Try changing the value of  $2\pi f$  and see how it affects the cyclotron performance.

- Now use the value  $2 \times 10^{-5}$  kg for the object's mass and see if you can get the cyclotron to work properly. (Remember that you will have to adjust the value of  $2\pi f$ ). **Let your instructor see this when it is working properly.**

## Lab 9: Magnetic Field Measurements

### Equipment:

1. Permanent bar magnet
2. Small compass
3. Helmholtz coils
4. Magnetic field sensor mounted on a rod clamped with table stand
5. 2 × 4 wooden block
6. Low voltage power supply
7. DMM (Ammeter)
8. Meter stick and small ruler
9. Computer with logger pro

### I. Introduction

In this exercise, you will examine the magnetic fields of two different magnets -- a permanent bar magnet and an electromagnet. The electromagnet is a Helmholtz Coil that consists of two identical circular coils of wire that are coaxial (have the same axis) and are separated by a distance equal to the coil radius.

The source of any static magnetic field is electrical current. In the case of the permanent magnet the current is simply the electrons orbiting the nuclei of the atoms in the metal bar, as well as the intrinsic current *within* the electron, associated with its “spin”. The current in the electromagnet is conventional current -- i.e., free electrons drifting under the influence of an electric field in the wires that make up the electromagnet.

#### a) Magnetic Field Maps

Magnetic field maps consist of a series of magnetic field lines -- lines that are everywhere tangent to the magnetic field direction. The direction of the magnetic field at a point in space is most easily determined by using a small compass. A compass needle will always point in the direction of the magnetic field. (**A note of caution:** small compasses are easily reversed-magnetized. Check often to make sure that your compass needle points north.)

A magnetic field line can be mapped by placing a compass at a point in the magnetic field and then moving the compass in the direction the needle is pointing. The path followed by the compass will be a magnetic field line.

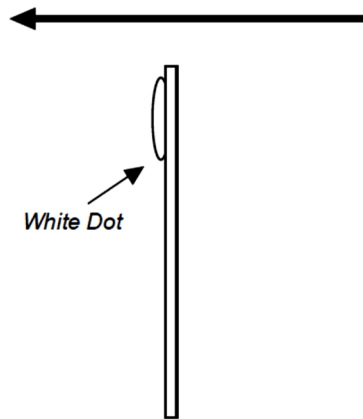
#### b) Magnetic Field Magnitude

Magnetic field magnitudes will be measured using a magnetic sensor whose operation is based on the Hall Effect. The sensor looks like a flat piece of plastic and is located in one end of a



transparent tube. The sensor measures the magnetic field component perpendicular to its plane. The positive direction for magnetic fields is shown in the following figure:

*This is the positive direction for magnetic fields*



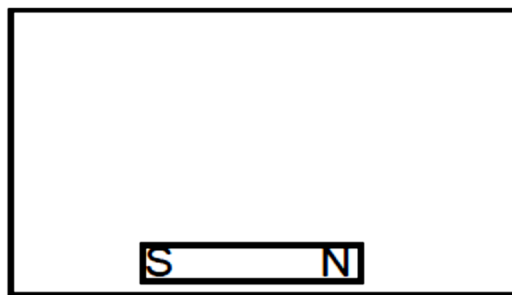
The sensor can measure magnetic field magnitudes up to 6.00 mT (milli-Tesla), which is 600 G (gauss) or 1200 times the earth's field. The sensor is interfaced with the computer program Vernier's Logger Pro to take data and plot it on several different types of graphs.

## II. Procedure

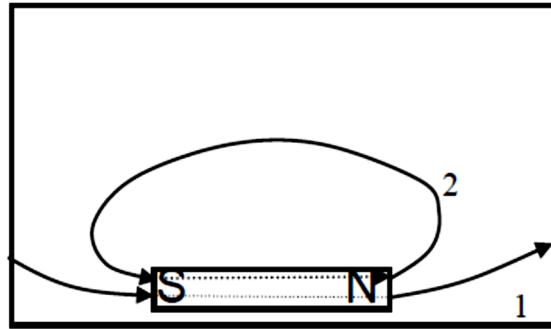
### a) Magnetic Field Maps

#### i) Bar Magnet

Place the bar magnet on one edge of a piece of paper as shown below. (Note that you are drawing only half of the two-dimensional field map of the magnet. By symmetry we would assume the other half to be identical to the one you construct.) Draw an outline of the bar magnet and be sure to indicate which end is the North pole and which is the South pole.



Use a compass (smaller one is better) to trace magnetic field lines as explained in section (1a). Place the compass near the North pole and move it in the direction the compass is pointing. Use a pencil to sketch the path followed by the compass. Two sample field lines are shown in the figure below.



Note that the field line labeled #2 in the figure is closed (i.e., it starts and ends at the same point). The dashed portion of this line actually passes through the metal of the bar magnet (you will **not** be able to sketch the dashed portion using a compass). All magnetic field lines are closed -- this is a general property of magnetic fields. Note also the arrows indicating the direction of the compass -- this is the magnetic field direction (from North to South, outside of the magnet).

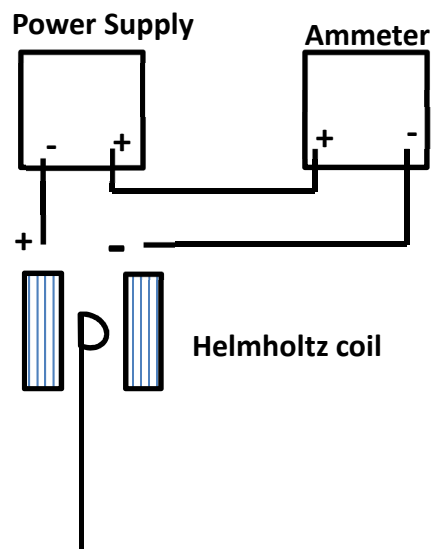
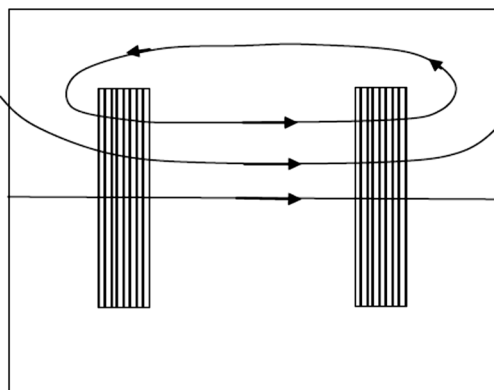
Field line #1 is also closed, but does not appear to be so because it goes off the edge of the paper.

Draw at least six magnetic field lines on your map. Include arrows indicating the magnetic field direction.

**ii) Helmholtz Coil**

Connect the Helmholtz Coil, the DC power supply, and the DMM set to function as an ammeter (on the 10.0 A range) in series. Turn the power supply on and set it to deliver a current of 1.00 amps. Use the compass to construct a map of the magnetic field of the Helmholtz Coil in the horizontal plane that passes through the centers of the loops. Sketch at least seven field lines.

A few sample field lines are shown in the figure below. Note the similarities and differences between this map and the map of the bar magnet.

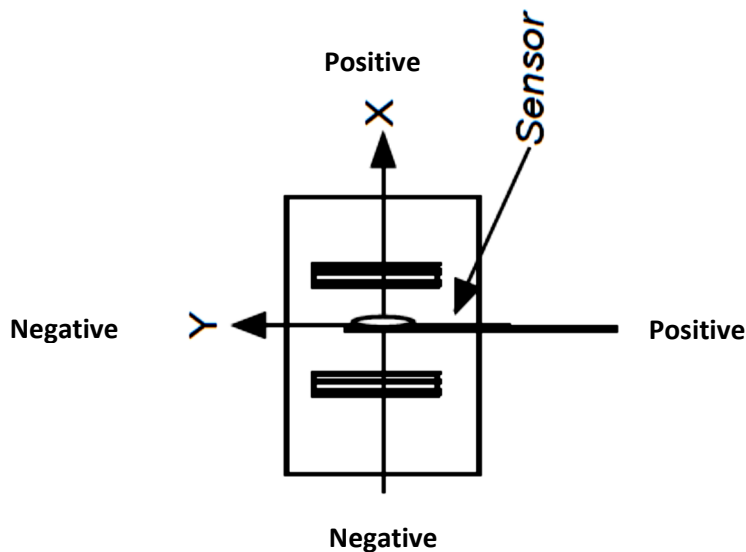


## b) Magnetic Field Magnitudes

You will now measure the magnetic field magnitude of the Helmholtz Coil as a function of current and as a function of position on the X and Y axes. In each of the following parts, the magnetic sensor will be oriented with its plane perpendicular to the magnetic field direction. It will thus measure the magnitude of the magnetic field (rather than some component of the field).

### i) B vs. I

Position the magnetic sensor so that it is on the X axis of the coils at a point midway between them (the origin of the X-Y coordinate system shown in the figure below). Orient the sensor so that its plane is perpendicular to the X axis. If the field measurements are negative, flip the sensor over. Since the magnetic field at the origin points in the X direction, the sensor will measure the field magnitude. Make the connections as shown in the figure.

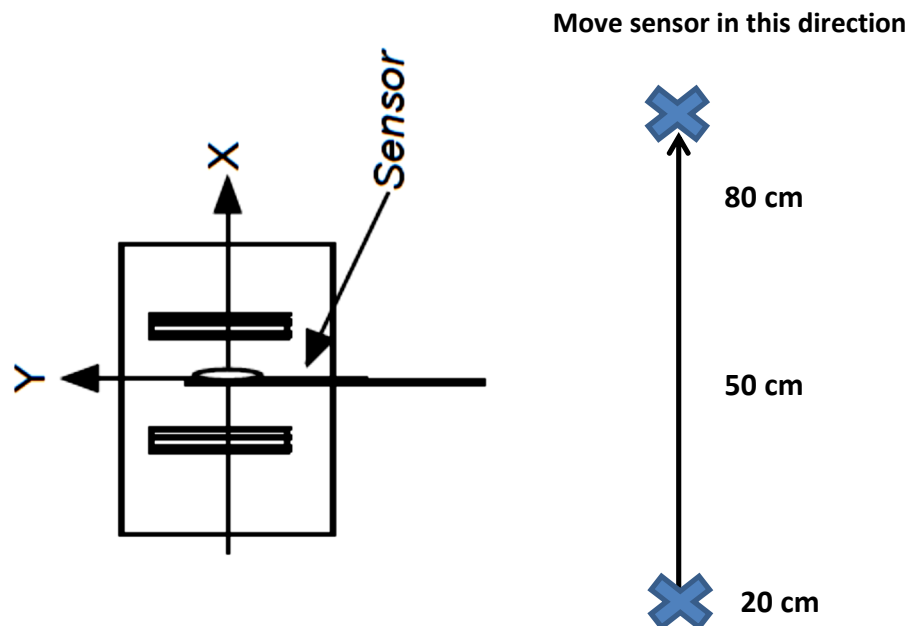


(You are here)

- Start the **Logger Pro** program.
- In order to have the computer plot magnetic field magnitude versus current, you must set the program for “Events with entry”. To do this, go to the EXPERIMENT menu and select Data Collection.
- When the New Window appears, click on the Mode and choose “Events with entry.” You will then be asked to define a new column for the variable you are going to enter, in this case, the current reading from the DMM. For the Full Name enter Current and for the Short Name enter I. For the units enter A. Click the OK box and a blank graph with magnetic field on the vertical axis and current on the horizontal axis will appear. Set the limits of the vertical axis scale from -2.5 mT to +2.5 mT. Set the horizontal axis scales from 0 to 1.50 A. Change point symbols use Graph options → Point symbols.

- Zero the magnetic field
- Click COLLECT and press Keep (to keep the field measurement).
- Enter current as zero and press ok
- Next increase current to 0.25 amps in DMM by increasing voltage on the power supply
- Click keep
- Enter current as 0.25 and press ok
- Next increase current to 0.5 amps in DMM by increasing voltage on the power supply
- Click keep
- Enter current 0.5 and press ok
- Repeat steps and go in increments of 0.25 A until you reach 1.50 A.
- You should now have a graph of B versus I.
- Go to the second row of the Menu, and choose “Linear Fit.” **Print out the graph-1 (Landscape)** with the curve fit information on it. [For this and all of the other graphs you will print out, include a title, axis labels and axis units.]

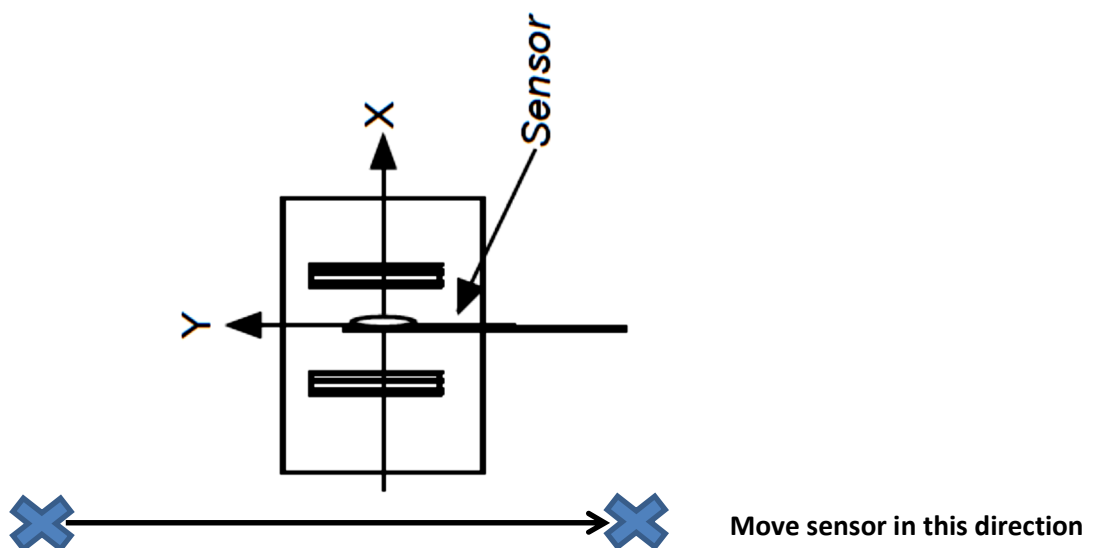
## ii) $B_x$ vs. X



- Go to the DATA menu and select “Clear all data”.

- Go to Data collection. Create a new “Events with entry” experiment, only now define a column for X position (use units of cm). The horizontal axis scale for X should range from 0 to 60 cm.
- Set the current to 1.00 A. This is the current that you will use for all the measurements in this section.
- With the magnetic sensor positioned at 0 cm shown in the Figure (Keep the long ruler in such a way that the central reading will be 30 cm).
- Click COLLECT and press keep (to keep the field measurement).
- Enter X as zero and press ok
- Now move the sensor to X = 5 cm position
- Click keep
- Enter X as 5 and press ok
- Next increase X to 10 cm
- Click keep
- Enter X as 10 and press ok
- Repeat steps and go in increments of 5 cm until you reach 60 cms
- You should now have a graph of  $B_x$  versus X position
- **Print out the graph-2 (Landscape)**

### iii) $B_x$ vs. Y



- Go to the DATA menu and select “Clear all data”.
- Go to Data collection. Create a new “Events with entry” experiment, only now define a column for Y position (use units of cm). The horizontal axis scale for Y should range from 0 to 60 cm with 30 cm in the middle.
- With the magnetic sensor positioned as in the previous section, set the current to 1.00 A. This is the current that you will use for all the measurements in this section.
- Click COLLECT and press keep (to keep the field measurement).
- Enter Y as zero and press ok
- Now move the sensor to  $Y = 5$  cm position
- Click keep
- Enter Y as 5 and press ok
- Next increase Y to 10 cm
- Click keep
- Enter Y as 10 cm and press ok
- Repeat steps and go in increments of 5 cm until you reach 60 cms
- You should now have a graph of  $B_x$  versus Y position
- **Print out graph-3 (Landscape)**

## Lab 10: Magnetic Induction

### Equipment:

1. Permanent bar magnet
2. Helmholtz coils
3. 6" heavy solenoid
4. Two 2 x 4 wooden blocks
5. Low voltage power supply
6. DMM (Voltmeter)
7. Voltage probe
8. Box filled with foam
9. Aluminum and Steel rods
10. Crocodile clips
11. Computer with Logger pro

### I. Introduction

If the magnetic flux through a circuit changes, for any reason, a voltage will be produced in the circuit. This is called magnetic induction. The circuit that we will use in this laboratory exercise is a solenoid and the external magnetic fields will be produced by a bar magnet and a Helmholtz Coil. The following equation gives the magnetic flux through a solenoid

$$\text{Mag. Flux} = (N) (B) (A) (\cos\theta),$$

where  $N$  is the number of turns in the solenoid,  $B$  is the strength of the magnetic field inside the solenoid,  $A$  is the cross sectional area of the solenoid, and  $\theta$  is the angle between the  $B$  vector and the solenoid axis. In order for this expression to be correct, the magnetic field should be uniform in magnitude and direction throughout the solenoid. In reality, this will only approximately be true.

The induced voltage will be measured by a voltage probe interfaced with the computer and the computer will display the voltage on a voltage versus time graph.

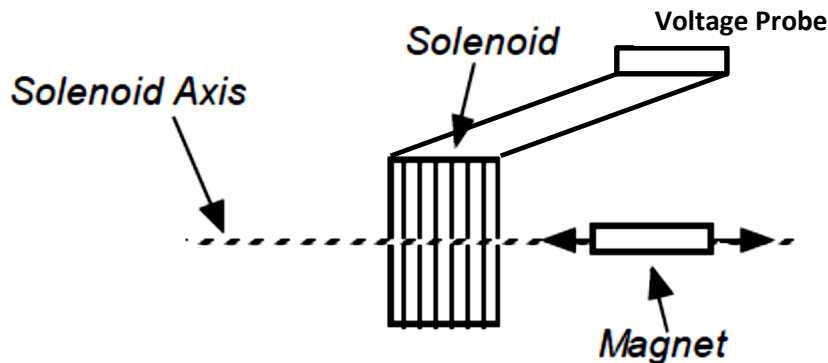
### II. Procedure

**All explanations should be written on the graph sheet.**

#### a) Bar Magnet

- Open the Logger Pro program. Set the display for one graph and zoom the graph to fill the screen. The graph should have voltage on the vertical axis and time on the horizontal axis. Set the vertical axis scale minimum to -1 V and the maximum to +1 V. The time limits should range from 0 to 10 s. **You should change the voltage and/or time scales at any point in this lab if it will help you see more clearly what is happening.**

- Go to the Data Collection icon (the stopwatch) and set the data collection rate to be 50 samples per second.
- With the voltage probe not connected, zero the system. Then, connect the voltage probes to the solenoid terminals and begin to take recordings of the voltage difference between the two ends of the solenoid.
- You are now ready to observe magnetic induction. Hold the bar magnet with its length parallel to and on the axis of the solenoid and close to but outside the solenoid.

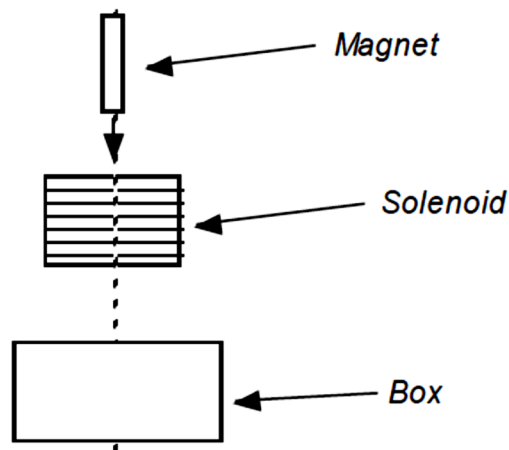


- Start the data collection and observe the voltage. As long as the magnet is not moved you should see no induced voltage. Now move the magnet into the solenoid -- do you see an induced voltage? **Print the graph-1.**
- Remember that any induced voltage is caused by a change in the magnetic flux through the solenoid. What is causing the change in magnetic flux?
- Move the magnet back out. How does the voltage induced while the magnet is moving out compare with the voltage induced when the magnet moved in? [Note: If the data collection stops at any time, simply restart it.]
- You will now move the magnet into the solenoid much faster than before. **Predict** how the flux change (and thus the induced voltage) will compare to the one produced when moving the magnet slowly. In particular, how will the amplitude of the induced voltage compare with that of the voltage induced before? How will the time duration of the voltage (the width of the voltage peak) compare? Perform the motion and **observe** the results. **Resolve** any differences between prediction and the observation. **Print the graph-2.**
- You will now observe the voltage induced by a magnet falling through the solenoid. Set the vertical axis scales to a minimum of -5 V and a maximum of +5 V. The time limits should range from 0 to 2 s. You will now use a data collection feature known as *triggering*. When this feature is active, data collection will begin only when it is triggered by certain values of the voltage. Go to EXPERIMENT → DATA COLLECTION menu or



CLOCK ICON and select TRIGGERING. Have the data collection trigger for  $\sim 0.01$  V and increasing slope. **This means you must drop the magnet through the solenoid so that the induced emf will be initially positive. Describe in your lab report what you had to do for that to happen.** Set up your experiment so that Logger Pro will store 20 samples of data prior to the trigger. This means that when the collection is triggered, Logger Pro will include the previous twenty data points in your table and on your plot, as well. Click OK. Once you have done this, hit the COLLECT button, and the program will wait for the “trigger” of seeing the voltage across the solenoid suddenly rising.

- Place the box with padding in it on the table. Have a team member hold the solenoid above the box with its axis vertical. Hold the bar magnet above the solenoid with its length parallel to the solenoid axis.



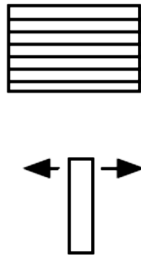
- Start the data collection and then, when you are ready to run your experiment, drop the magnet and allow it to fall completely through the solenoid. Have another team member make sure that the magnet doesn't bounce out of the box and hit the floor or the table. (These magnets break easily.)
- Observe the voltage versus time graph. Did the triggering work correctly?

**Print out the graph-3.**

Can you explain the shape of the induced voltage (think about the change in magnetic flux)? You will now drop the magnet again from a greater height above the solenoid. Predict how the new graph will compare to the previous one. Perform the drop and observe the results. Resolve any differences between observation and prediction. How could this system be used to measure the velocity of a falling magnet?

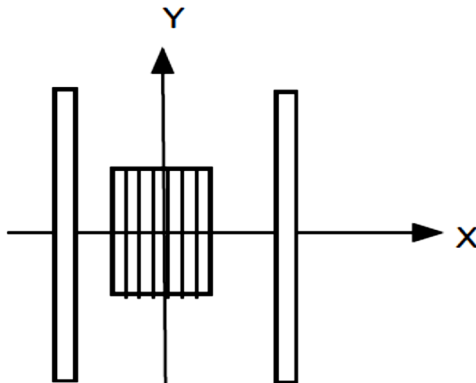
After removing triggering, change the vertical axis limits to  $-0.2$  V and  $+0.2$  V and change the time limits to  $0 \rightarrow 10$  s. With the solenoid back on the table and with its axis horizontal, hold the magnet with its length along the solenoid axis so that the magnet is about 10 cm from the solenoid. You are going to shake the magnet back and forth as shown in the figure below. Predict what the induced voltage will look like. Perform the motion, **Print the graph-4** of induced

voltage, and give its peak amplitude. How far from the solenoid can you hold the shaking magnet and still see an induced voltage?



### b) Helmholtz Coil with DC Current

Place the solenoid in the center of the Helmholtz Coil in such a way that its axis coincides with that of the Helmholtz Coil. Make sure also that the center of the solenoid coincides with the center of the Helmholtz Coil. The diagram shows the coil looking down from above it.



Connect the Helmholtz Coil to the DC side of the power supply and set it to produce a current of 1.00 A. Set the vertical axis scale limits of the Voltage-Time graph to - 0.5 V and +0.5 V. Start the data collection. Don't move anything -- simply observe the voltage. What do you think is causing this induced voltage? (This is often called "background" or "noise" voltage.)

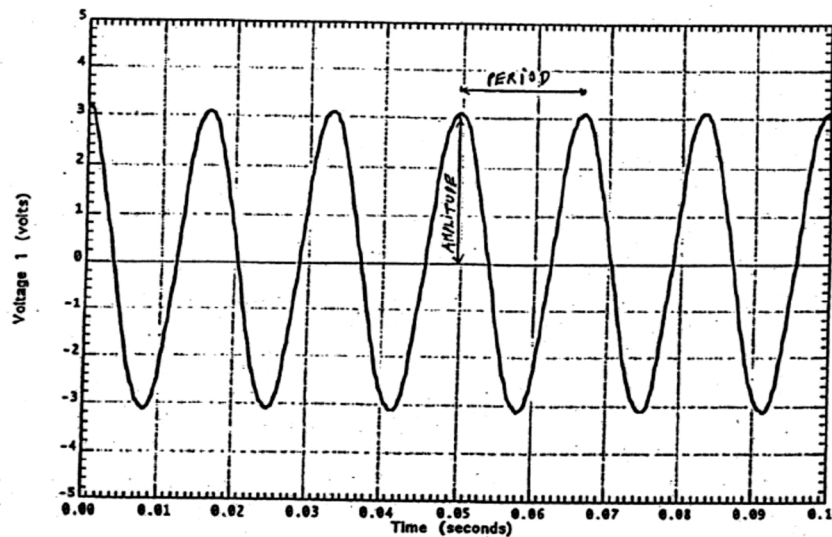
Observe the voltages induced by the following case and explain what is causing the magnetic flux to change. No graph printouts here. Only observation and comments.

- Hold the steel rod inside the solenoid and parallel to and on the X axis. Observe the induced voltage for various motions of the rod. Does the voltage increase as the rod moves faster? Does the distance between the rod and the center of the solenoid have any effect on the voltage? Do the same thing with aluminum rod.

### c) Helmholtz Coil with AC Current

Describe what you measure, and explain what you observe on the graph sheet.

- We have not encountered alternating voltages in this laboratory before today so we will take a few minutes to examine the basics. With the power supply turned off, connect the voltage probe directly to the AC output (the red jacks on the right hand side) of the power supply. Set the AC voltage to 2.0 volts. (When you check this with your DMM, make sure you are using the AC setting. The value given is the *rms*, or root mean square value of the voltage)
- Go to EXPERIMENT → DATA COLLECTION menu and set the Data Collection Rate to 3333 samples/sec (or whatever the maximum is for your probe sensor). You won't be able to do so until you reduce the duration of your experiment to something manageable, such as the recommended 0 to 0.10 seconds. Set the data averaging (File->Settings for untitled) to 9 point averaging (smoothing and derivative). Set the vertical axis limits to - 5 V and + 5 V and set the time axis limits to 0 and 0.10 s (1/10 s.). When you start the data collection, you will notice that nothing appears on the screen until after all of the data is collected. In other words, you will not see real time display of the data. You will see a *delayed time* data display, which is normal for older equipment. Turn on the power supply and start the data collection. You should see a sinusoidal graph similar to the one shown below.



This is a typical alternating (often called AC) voltage. Two important parameters of an alternating voltage are shown in the figure -- the zero-to-peak **amplitude** (A) and the **period** (T). The **frequency** (f) of the voltage can be found using the following relationship:

$$f = 1/T$$

The units of T are seconds/cycle and the units of f are cycles/sec = Hertz = Hz.

- **Print the alternating voltage graph-5** and measure A and T. Calculate f (it should be very close to 60 Hz). Record all the information on the graph sheet.

- What happens to the amplitude, period, and frequency when the power supply setting is changed to 4.0 V?
- Return the power supply setting to 2.0 V. Connect the solenoid to the voltage probe and place the solenoid at the center of the Helmholtz Coil (as you did in part (2)). Connect the Helmholtz Coil to the AC side of the power supply. Note that the induced voltage is caused by the time-varying B-field and not the movement of the coil.
- Predict what the induced voltage versus time graph will look like. In particular, will the induced voltage also be alternating voltage? Will it have the same frequency as the power supply voltage? Start the data collection. Does observation agree with prediction? Measure and record the amplitude of the induced voltage. **Print the graph-6**
- With the solenoid at the center of the Helmholtz Coil, observe the amplitude of the induced voltage when the solenoid axis is at a 45 degree angle to the Helmholtz Coil axis. Do your results agree with the fact that the flux through a solenoid contains the factor  $\cos \theta$  (where  $\theta$  is the angle between the magnetic field direction and the solenoid axis)? **Print the graph-7.**
- Also observe for a 90 degree angle. **Print the graph-8.**
- Finally, return the solenoid to the center of the H. Coil with its axis parallel to the axis of the Helmholtz Coil. Place the steel rod inside the solenoid and observe the amplitude of the induced voltage. **Print the graph-9.**
- Repeat using the aluminum bar. **Print the graph-10.**

## Lab 11: Microwaves

In this lab you will perform several experiments using microwave transmitters and detectors. The main purpose of this lab is to verify the electromagnetic wave nature of microwave radiation. We will use a two-slit diffraction experiment to get an estimate of the wavelength of the microwaves, and then observe the waves as they reflect off or are transmitted through various materials. You should be able to explain the various phenomena you observe in terms of the interaction of electromagnetic waves and electric charges.

### I. Apparatus

The experimental apparatus is not identical, so please allow for some variations with the description of the apparatus given below. We have available Gunn diode or Klystron tube microwave transmitters and receivers that record the power of the detected radiation. The transmitters and receivers have metal horns which guide the waves so that in the intervening space they are roughly plane waves. The transmitters and receivers have slots underneath them so that they can be fitted on the rotating arms of the goniometer, which will be used to measure angles of incidence and reflection.

### II. Measurement of the wavelength

In this part you are to use a two-slit diffraction grating to determine the wavelength of microwaves generated by your transmitter, and in so doing verify the wave nature of the radiation. The two slits serve as two sources of microwave radiation that are in phase, and separated by a distance,  $d$ , which is measured from slit center to slit center. By observing the locations of minima and maxima in the interference pattern produced from the radiation of these two sources, we can find the wavelength of the radiation using the following arguments. Consider the diagram drawn below.

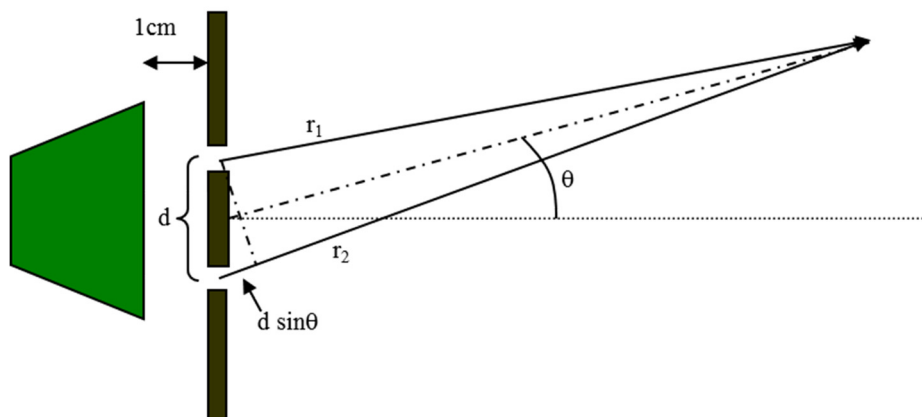


Fig. 1

Note that as long as the observation point is much farther away than the separation distance,  $d$ , we can approximate the difference in path length as  $\Delta r = d \sin \theta$ . From our study of 2-D waves in chapter 17, we showed that

$$\Delta r = d \sin \theta = m\lambda, \quad (1)$$

where  $m = 0, 1, 2, 3$ , etc. identifying the interference maxima located at angle  $\theta$  with respect to the central line shown in Fig. 1, and  $d$  is the distance between the centers of the two slits. The apparatus should be set up as in Fig. 2 below.

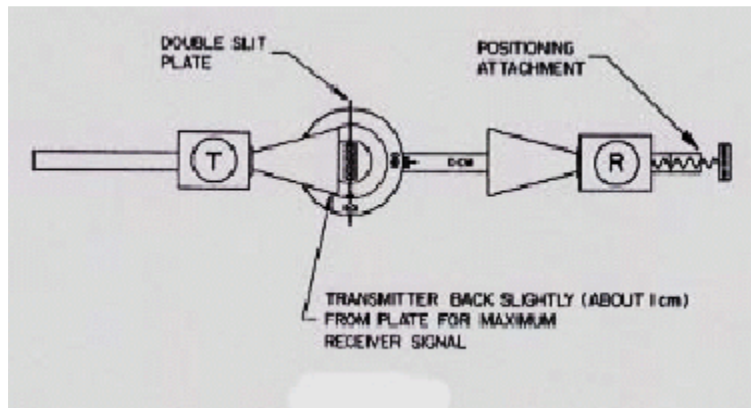


Fig. 2. Set-up for double slit interference

Adjust the plate, transmitter and receiver while they are directly facing each other to maximize the signal read out on the transmitter up to about 90. Adjust the protractor so that the  $0^\circ$  mark is pointing at the receiver, and the  $180^\circ$  mark at the transmitter. This is the location of the central maximum. Now, slowly and smoothly rotate the arm on which the receiver is resting to the right, all the while observing the power readout. Record the power reading as a function of  $\theta$  for every  $5^\circ$  until you are past the second maximum. Find the maximum positions by fine tune. Then take more closely spaced readings near the first and second peaks. Determine your experimental value for the angle of the two maxima, as well as the estimated accuracy of your measurement. Rotate the arm the opposite direction and repeat the procedure. Average the two angles obtained for the  $m = 1$  and  $m = 2$  maxima and, using Eq. 1, calculate the wavelength of the microwave radiation.

What is your estimated error for your experimental value of  $\theta$ ? Which of the two angles do you think gives you the better estimate of  $\lambda$ ?

### III. Reflection of microwaves by a flat conducting surface

In this experiment you will verify the law of specular reflection for microwaves, i.e.,  $\theta_i = \theta_r$ . The reflecting surface we will use is a solid aluminum plate which can be fitted into the plate holder. Set up your apparatus as in Fig. 3.

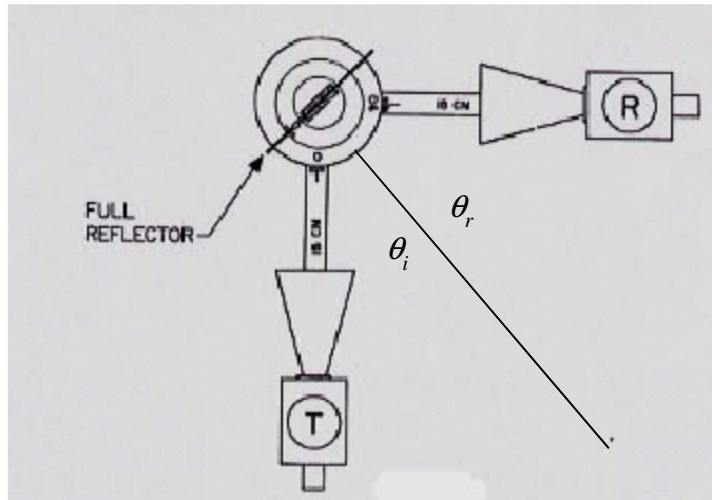


Fig. 3. Sample set up for specular reflection

Orient the transmitter and reflecting plate for an angle of incidence of  $45^\circ$ . Find  $\theta_r$ , the angle at which the maximum signal is received with respect to the normal. In addition, record the reflected power as a function of  $\theta_r$  to  $20^\circ$  on either side of the observed maximum. Draw a graph showing power vs.  $\theta_r$ .

Does the law of specular reflection hold for microwave radiation? Explain why there is some radiation observed at angles near but not at  $\theta_r$ . Hint: What if the radiation produced by the source is not exactly a plane wave?

#### IV. Forward and backward scattering

Keep your apparatus set up as in Fig. 3, with the angles of incidence and reflection both at  $45^\circ$ . Replace the solid aluminum plate with the polarizer plate (See appendix A.). Orient the slits of the plate horizontally, next at  $45^\circ$ , and then with the slits vertical. Record the power *reflected* from the plate in each case.

Next, orient your apparatus as in Figure 4. Using the same three orientations of the slits used in the reflection experiment in Section III, measure and record the transmitted power.

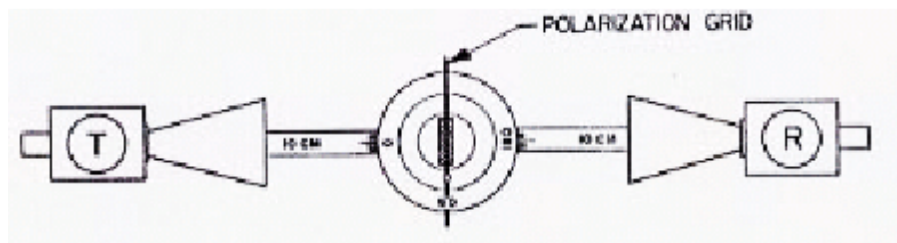


Fig. 4 Transmission through a polarizing plate.

Both the Gunn diode and klystron tube transmitters produce microwaves that are polarized so that the E-field is aligned along the vertical direction. (In the Gunn diode, for example, the waves are produced by an alternating current in a vertically aligned diode acting as a dipole-like antenna.) Are your observations what you expected?

Explain why the horizontally aligned plate reflects no radiation but passes all of it, in terms of its effectiveness as a scatterer of vertically polarized EM waves. From our discussion in class, use the model of a free electron in the vertically aligned metal bars to show why the backward scattered wave is large, while the forward scattered wave acts to cancel the transmitted wave.

### V. Microwave absorption

In this experiment, you will determine the amount of microwave radiation absorbed by various materials by measuring the total amount of radiation reflected and transmitted by various substances and subtracting that from the total power transmitted by the source. Set up your apparatus as in Fig. 5.

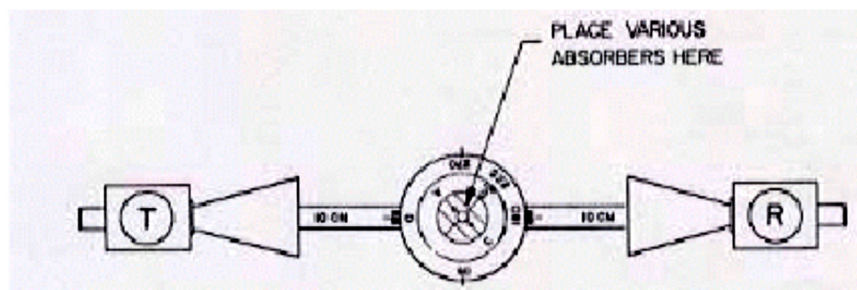


Fig.5. Set up for microwave absorption experiment.

Record the power transmitted through a *solid metal plate*, a *half-reflector*, a *piece of plywood*, the *empty Lucite water box*, with each of the objects oriented as in Fig. 5. Next, move the receiver to the  $270^\circ$  mark as in Fig. 4. Record the power reflected from each material. The power absorbed by each of the materials is the difference between the power received by the unobstructed receiver and the sum of the transmitted and reflected powers for each of the objects. Record these in a table. Explain the differences, briefly.

Now, fill the Lucite water box with water, and record the reflected and transmitted power. What is the power absorbed by the water?

Explain the water absorption of microwaves in terms of the effect of the radiation on the water molecules. Where does the absorbed radiation energy go? Why are microwaves such efficient cookers of food?



## Lab 12: AC Circuits

### Equipment:

1. 60-Hz AC power supply (function generator)
2. Two dmm's
3. Two Vernier voltage probes
4. One Vernier current probe
5. One LCR meter
6. One Pasco RLC circuit board.
7. Crocodile clips
8. Short and long wires

### Discussion: RLC circuits with an AC power supply

The RLC series circuit combines in series all three circuit elements discussed in class thus far.

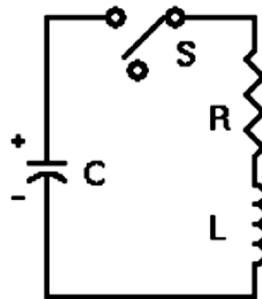


Figure 1: Capacitor discharging through an RLC series circuit

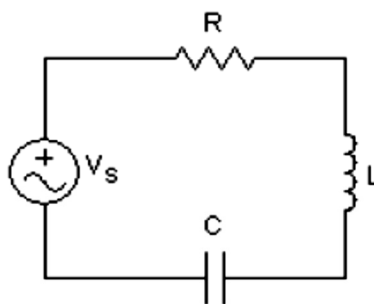


Figure 2: An AC power supply driving a sinusoidal current through an RLC series circuit.

### DC Circuits:

There are two scenarios we consider in detail in class. The first is illustrated in Figure 1. A capacitor  $C$  has been charged to some initial potential  $V_0$ , and then the switch  $S$  is closed so that the capacitor discharges through the resistor,  $R$ , and inductor,  $L$ . The behavior of the current in

the circuit and charge on the capacitor depends on the resistance in the circuit. If the resistance is relatively small, then the circuit behaves to first order like an LC circuit in which the current (and the charge on the capacitor) oscillates sinusoidally in magnitude and polarity with frequency

$$\omega_0 = \sqrt{\frac{1}{LC}}$$

The presence of the resistance in the circuit results in an exponential decay of the current amplitude (and charge) with time, as energy is dissipated through the resistor while the current oscillates sinusoidally. It also causes the frequency of the oscillations to be reduced slightly, so that

$$\omega_d = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

This type of system is called an under-damped oscillator. A larger resistance means that the rate of decay of the current amplitude increases until all of the energy stored in the capacitor is dissipated in the resistor in the course of one oscillation. This is called a critically-damped RLC circuit. Still larger resistance leads to behavior that is called over-damped.

### AC circuits:

In the second scenario, shown in Figure 2, the circuit is being driven by a sinusoidally-varying power supply with frequency  $\omega=2\pi f$ , such that

$$\mathcal{E}(t) = \mathcal{E}_{\max} \sin(\omega t + \phi)$$

The factor  $\phi$  is the **phase** of the voltage coming from the power supply. Phase is important when you have two oscillations or waves with different phases. For this series circuit, the second oscillating quantity is the current,

$$i(t) = i_{\max} \sin(\omega t)$$

In general, while the current and voltage in RLC circuits have the same frequency, the voltage across the power supply is **OUT OF PHASE** with the current flowing through the circuit. The graph below illustrates this situation.

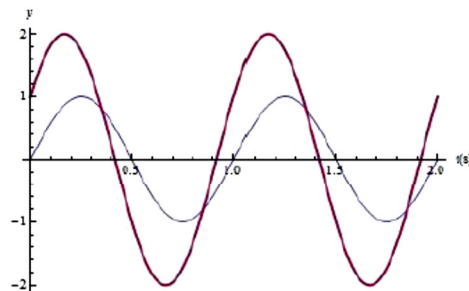


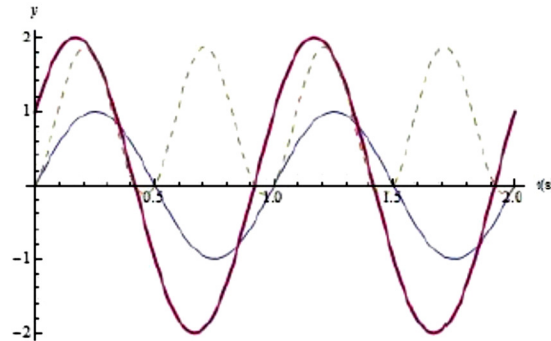
Figure 3: Two sinusoidal functions have the same frequency of  $2\pi$ , but the darker curve is *leading* (reaches its peak earlier) the lighter curve by a phase angle of  $\pi/6$  radians (or  $30^\circ$ ).

**Power:**

The power delivered to the circuit by the power supply at any instant is just

$$\mathcal{P}_{inst}(t) = \varepsilon(t)i(t).$$

The graph below illustrates this product for two sinusoidally varying quantities.



**Figure 4:** The dashed curve represents the instantaneous power being delivered to the circuit.

Notice that the power delivered has a maximum that is lower than you would expect just by multiplying the amplitudes of the two functions. However, if we *average the power* over the period of the oscillation,  $T = \frac{2\pi}{\omega}$ ,

$$P_{avg} = \frac{1}{T} \int_0^T \varepsilon_{max} \sin(\omega t + \phi) i_{max} \sin(\omega t) dt = \frac{1}{2} \varepsilon_{max} i_{max} \cos \phi$$

we see that the average power is related to the expected maximum power, except for a factor of  $\frac{1}{2}$ , and the cosine of  $\phi$ , the phase angle.

**RMS quantities:**

The factor of  $\frac{1}{2}$  results from the fact that the current and voltage are always oscillating about zero (0). This factor is taken into account by using the “rms” or “root mean square” values of the voltage and current,

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T (\varepsilon_{max} \sin(\omega t + \phi))^2 dt} = \frac{\varepsilon_{max}}{\sqrt{2}},$$

$$i_{rms} = \sqrt{\frac{1}{T} \int_0^T (i_{max} \sin(\omega t + \phi))^2 dt} = \frac{i_{max}}{\sqrt{2}}.$$

When you use a DMM to measure the voltage or current in some part of an oscillating circuit on its AC setting, it will display the *rms* value. Expressed in terms of the *rms* values, the average power is then

$$\mathcal{P}_{avg} = V_{rms} I_{rms} \cos\phi.$$

### Reactance:

The factor of  $\cos\phi$  tells us that the power delivered is a maximum when the phase angle  $\phi=0$ , while the average power goes to zero when the phase angle is  $\phi=\pi/2$ ! Obviously, the phase angle between current and voltage plays a huge role in determining whether any electrical power is delivered by the circuit. Therefore, we need to understand: *what determines the phase difference between the current and voltage?* The fundamental reason for this phase difference in an RLC circuit is the way voltage drops are established across each of the three components.

As in DC circuits, the instantaneous voltage drop across the **resistor** is just

$$V_R(t) = i(t)R = i_{\max} R \sin(\omega t).$$

The voltage amplitude across the resistance is therefore

$$V_R = i_{\max} R.$$

For the inductor and capacitor, however, the voltage across them is only indirectly related to the current in the circuit.

The voltage drop across the **inductor** is proportional to the rate of change in the current, and reacts to oppose all changes in current. As a result, the voltage across the inductor **leads** the current in the circuit by a phase of  $\pi/2$ :

$$V_L(t) = L \frac{di}{dt}(t) = i_{\max} \omega L \sin\left(\omega t + \frac{\pi}{2}\right).$$

The voltage amplitude across the inductance is proportional to the maximum current, just like the voltage across the resistance. The constant of proportionality has units of ohms ( $\Omega$ ), but is called the “**inductive reactance**”:

$$\chi_L = \omega L$$

The voltage amplitude across the inductor is therefore

$$V_L = i_{\max} \omega L = i_{\max} \chi_L$$

The voltage drop across the **capacitance** is proportional instead to the build-up of charge across it as a cumulative result of the current flow, and reacts to oppose that build up. As a result, the voltage across the capacitor **lags** the current in the circuit by a phase of  $\pi/2$ :

$$V_C(t) = \frac{q(t)}{C} = \frac{i_{\max}}{\omega C} \sin\left(\omega t - \frac{\pi}{2}\right).$$

The voltage amplitude across the capacitance is also proportional to the maximum current. The constant of proportionality here is called the “**capacitive reactance**”:

$$\chi_c = \frac{1}{\omega C}.$$

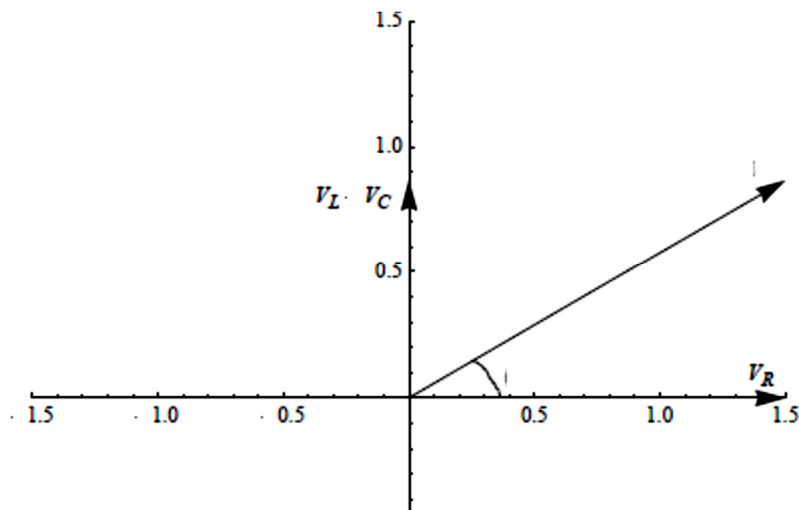
The voltage amplitude across the capacitance is then:

$$V_c = \frac{i_{\max}}{\omega C} = i_{\max} \chi_c.$$

Reactance has the same unit as resistance, *ohms*, and determines the relationship between current and voltage, just like resistance. However, unlike resistance, reactance does not dissipate electrical energy. It stores that energy in the magnetic field of the inductor and/or the electric field of the capacitor, and then reintroduces that energy back into the circuit. This process of energy extraction and then re-insertion occurs at the same frequency as that of the current, but is  $90^\circ$  out of phase with the current. Also, unlike resistance, reactance depends on the frequency,  $\omega$ , of the current oscillation.

### Phase Angle:

The AC voltage across the RLC circuit is the sum of the instantaneous voltages across the three components. This sum involves three sine functions with different phases. One way to handle this sum is to think of each voltage as the vertical component of a vector-like quantity called a *phasor*, each of which has a magnitude equal to the voltage amplitudes ( $V_R$ ,  $V_L$ ,  $V_C$ ), and an angle in phasor space ( $\omega t$ ,  $\omega t + \pi/2$ ,  $\omega t - \pi/2$ ). The voltage across the entire circuit,  $\varepsilon(t)$ , would then be the vertical component of the “vector sum” of the three individual phasors. The (constant) phase difference between  $\varepsilon(t)$  and  $i(t)$  would be the (constant) angle in phasor space between the  $\varepsilon$  phasor and the  $V_R$  phasor.



The net result is the following expression for the *phase difference*,

$$\phi = \tan^{-1} \left( \frac{\chi_L - \chi_C}{R} \right) = \tan^{-1} \left( \frac{\omega L - \frac{1}{\omega C}}{R} \right)$$

This is the phase angle by which the power supply voltage leads the current.

### Impedance-Z:

Using the result from the phasor analysis outlined above, the *rms* (or max) voltage across the entire circuit,  $V_{rms}$ , can be obtained by combining the voltage amplitudes for each circuit element using Pythagoras' theorem:

$$V_{rms} = \sqrt{(I_{rms}R)^2 + I_{rms}^2(\chi_L - \chi_C)^2} = I_{rms}Z$$

$$Z = \frac{V_{rms}}{I_{rms}} = \sqrt{(R)^2 + (\chi_L - \chi_C)^2}$$

The quantity  $Z$  is called the “impedance.” The impedance represents the effective “resistance” of a circuit to an AC voltage. Like reactance, impedance depends on the angular frequency,  $\omega$ , with which the circuit is being driven.

### Resonance:

As can be seen from both the expressions for the phase angle  $\phi$  and the impedance  $Z$ , the difference between the inductive and capacitive reactance,  $\chi_L - \chi_C$ , is an important quantity. The sign of this difference determines whether the voltage leads or trails the current in phase. The minimum value of impedance is obtained when this difference is zero. In fact, when  $\chi_L - \chi_C = 0$ , the impedance simplifies to

$$Z_{resonance} = R.$$

A minimum value of the impedance  $Z$  means the largest possible  $I_{rms}$  for a given  $V_{rms}$  from the power supply. In addition,  $\chi_L - \chi_C = 0$  means that the phase angle  $\phi = 0$ . Therefore, the contributions to the voltage from the capacitor and inductor exactly balance. This condition is called **resonance**. Recall from our discussion of the power that  $\cos\phi=1$  corresponds to the maximum power delivered from the power supply,

$$\mathcal{P}_{avg,resonance} = V_{rms}I_{rms}.$$

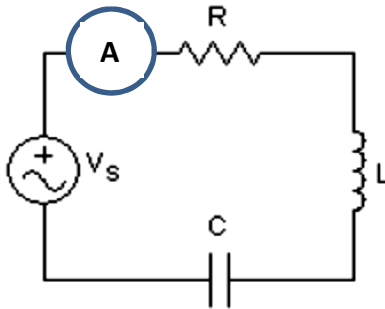
For a given capacitance,  $C$ , and inductance,  $L$ , all this occurs for the special value of driving frequency,

$$\omega_0 = \sqrt{\frac{1}{LC}}$$

This is the frequency of oscillation for a pure LC circuit.

### **Experiment I: RMS Measurements:**

In this first experiment, you will work with the Pasco circuit board, the AC power supply (function generator), voltmeter and ammeter. The Pasco circuit board shows you the connections which are hardwired underneath. We will use the  $10\ \Omega$  resistor, the  $8.2\ \text{mH}$  inductor, and the  $100\ \mu\text{F}$  capacitor. If you hook up your power supply ( $\sim 1000\ \text{Hz}$ ) starting at the capacitor and ending at the resistor, you will have an RLC series circuit. Although the values marked on the board are pretty accurate to 2 significant figures, there is a significant omission in that they don't tell you the resistance across the inductor. This value is  $R_{\text{inductor}} = 5.3\ \Omega$ , and is large enough to make an impact on your measured values.



The DMM's should be set to measure AC values. Remember that this means it will report *rms* (root mean square) values. You should hook up the DMM to measure current as it comes out of the power supply, starting from the low impedance output plug. Set your scale to 200 mA. The DMM for measuring voltage should be connected so as to measure the voltage from one end of the RLC circuit board to the other. Set that scale to 20 V. With the function generator off, connect the wire coming from the DMM measuring current to the plug underneath the  $100\ \mu\text{F}$  capacitor. Connect the ground plug from the function generator directly to the plug underneath the  $10\ \Omega$  resistor.

#### **(a) Determine the impedance, $Z$ :**

- Before turning on the power supply, make sure that the voltage is set to 0. Then turn on the power supply and increase the amplitude of your signal from the function generator

until  $V_{rms}$  is 2.00 V (or  $V_p=2.83V$ ). Record your  $I_{rms}$  current reading. Then calculate the total impedance,

$$Z = \frac{V_{rms}}{I_{rms}}, \text{ of your circuit.}$$

- Now, determine the predicted values of  $Z$  and  $I_{rms}$  using the formulas given above with the component values of R, L and C, and compare with your measured values. Remember to include the additional resistance present in the inductor! Since the components are in series, the resistance of the inductor is simply added to the resistance of the 10  $\Omega$  resistor. Also, remember that the signal frequency,  $f$ , shown on the function generator is in hertz (Hz), while  $\omega=2\pi f$  is in radians per second. Do your values agree? **At this point, check with your instructor.**

**(b) Find the voltages across the individual components:**

- Now, check whether your measured values of  $V_{rms}$  across the three components match the predicted values. Using your DMM that was measuring the voltage across the entire circuit, measure the voltage across each of the circuit components, and compare with the expected *rms* voltages using the formulas given in the discussion section. They should all agree quite well, except in the case of the inductor. In general, you should see the voltage drop across the inductor to be greater than what is predicted from the inductance alone. Now, you might think to add the expected voltage drop across the resistance in the inductor to the voltage drop across the inductance. Does that agree with your measured value? Discuss why or why not. **At this point, check again with your instructor.**

**Experiment II: Computer measurements**

It is quite difficult to isolate the inductance in our RLC series circuit from the resistive portion of the circuit. On the other hand, the resistor and the capacitor do behave as single components in the circuit. You will take advantage of this fact in carrying out the next set of experiments.

Remove both the DMMs from your circuit. Keep the power supply setting at 2.0 V rms.

**Warning: IMPORTANT!!** *In all previous DC circuits, we paid little attention to which connection went to ground. But when it comes to AC circuits, it is very important to know which connection goes to “true” ground. Therefore, you MUST connect all grounded wires at only one point in the circuit! If you connect two points in the circuit to ground you will bypass all or part of your circuit, changing the behavior of the circuit dramatically. This is a crucial point. Failure to identify where your ground is will be the most likely cause for error and confusion as you carry out your measurements.*

We will use the two Vernier voltage probes as well as the current probe in our measurements. The current probe isn't grounded, but the voltage probes are. The power supply may be grounded as well. Plug in your probes. Set your Logger Pro data settings to collect data over a 0.1 second interval and up to 30 secs, and then to collect the maximum number of data points possible in that



interval. Introduce your current probe in series with the rest of the circuit. Place one voltage probe in parallel to the entire circuit. Have your instructor check your circuit before proceeding.

### Voltage and current vs. time on the computer

Now, you are ready to begin using Logger Pro to see the behavior of your AC circuit. Hit Collect so that the readings of your voltage and current probes are displayed. You should be able to see the oscillating voltage signal across your series circuit. Record your maximum voltage for the circuit as displayed on the screen, and verify that it has the correct relationship with the value of  $V_{rms}$  previously measured on your DMM. Also, measure the time for one full oscillation of your signal. Multiply this time value with a **calibration constant**  $0.0709 \times 10^{-3}$  and make sure that time matches with the period ( $T = 1/f$ ) of the signal coming from your function generator.

Is the source voltage signal from the power supply leading, lagging or in phase with the current?

Take a print of the graph. (**PRINT-LANDSCAPE**)

**Phase Angle** - In order to measure the phase angle between the current and the power supply voltage, you need to measure the difference in time,  $\Delta t$ , between the curves (power supply voltage peak and current peak) and then compare that time to the period,  $T$ , of one oscillation. One oscillation is equivalent to  $2\pi$  radians or  $360^\circ$ . Therefore, the phase shift in degrees can be found from

$$\phi = 360^\circ \cdot \frac{\Delta t}{T}.$$

The sign of the phase angle is determined by whether the voltage is leading (+) or lagging (-) the current (voltage through the resistor). Now, compare your measured value of the phase angle with the calculated value from the formula for  $\phi$  (page 6) given in the introduction. Don't forget to include the additional resistance you found in the inductor! Add it to the  $10 \Omega$  resistance.

Place the other voltage probe across the  $10 \Omega$  resistor only. Next, look at the voltage across the  $10 \Omega$  resistor on your board. Record the maximum voltage across the resistor and compare that value with the *rms* voltage you measured earlier using the DMM. Hit Collect so that the readings of your voltage and current probes are displayed.

Is the voltage across the resistor leading, lagging or in phase with the current?

Take a print of the graph. (**print-landscape**)