<table>
<thead>
<tr>
<th>Week</th>
<th>Dates</th>
<th>Notes</th>
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<td>19-Jan</td>
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<td>26-Jan</td>
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</tr>
<tr>
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<td>2-Feb</td>
<td>Lab 2</td>
</tr>
<tr>
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<td>9-Feb</td>
<td>Lab 3</td>
</tr>
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<td>Lab 3</td>
</tr>
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<td>2-Mar</td>
<td>Lab 5</td>
</tr>
<tr>
<td>9-Mar</td>
<td>9-Mar</td>
<td>Review and Lab Make Up</td>
</tr>
<tr>
<td>16-Mar</td>
<td>16-Mar</td>
<td>No lab this week- First Midterm</td>
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<td>13-Apr</td>
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<td>27-Apr</td>
<td>Lab 9</td>
</tr>
<tr>
<td>4-May</td>
<td>4-May</td>
<td>Review and Lab Make Up</td>
</tr>
<tr>
<td>11-May</td>
<td>11-May</td>
<td>FINALS</td>
</tr>
</tbody>
</table>
Laboratory Instructions

General considerations:

- You must come prepared to the lab. Read the laboratory guide in advance to understand the activity you will perform.
- You will be part of a team with other students. Each team is responsible for the report.
- Teams will be assigned by the TA the first day of class.
- PRINT the laboratory guide BEFORE going to your lab section.
- Solve exercises indicated in the guide.
- Turn it in to the TA at the end of the lab section.
- If you are not able to complete the assignment in the allowed time, arrange with the TA a make up session in the weeks indicated in the lab schedule.
- EACH group must turn in one lab report.
- Read the operation manuals for the equipment before using it. Ask the TA if you have questions.
- The labs are mandatory. You must have all your lab reports completed in order to pass the class.
Objective: You will be introduced to basic use of MATLAB

Introduction
We will introduce the very basic concepts using a powerful software package called MATLAB®. This is a high performance language that integrates computation, visualization and programming. MATLAB stands for matrix laboratory. The program easily handles matrixes and vectors and has a powerful graphic package to display magnitudes in 2 and 3 dimensions.

MATLAB language is specially oriented to calculations with vectors and matrixes. To perform calculations with these elements is straightforward. It is especially useful for algorithm development, data visualization, data analysis, and numeric computation. Using MATLAB you can solve technical computing problems faster than with traditional programming languages.

You can use MATLAB in applications like signal and image processing, communications, control design, test and measurement, etc.. Add-on toolboxes (collections of special-purpose MATLAB functions, available separately) are also available to solve particular classes of problems.

Starting/Quitting
To start MATLAB, click on the ‘Start’ button on the left bottom of the screen, and then click on ‘All Programs’, then ‘Math Software’, then ‘MATLAB’. A window will pop up that will consist of three smaller windows. On the right there will be a big window entitled ‘Command Window’. On the left there will be two windows, one entitled ‘Workspace’ and another one ‘Command History’.
To use MATLAB, you will mostly be typing in the ‘Command window’ but you also create files in an editor and save them. Click on the Command window. Its outline will become dark (that’s how you know that you can type into that window). A cursor will start blinking on a line right after ‘>>’ (this is called a prompt). You can start typing your statements.

**MATLAB as a calculator**

MATLAB operations are designed to work with matrixes. Special cases are 1x1 matrixes (scalars) or matrixes with only one row or column (vectors). For example the instruction

5*3

MATLAB will give us

ans =

15

The variable “ans” stores the result of the last calculation. It will be overwrite in the next calculation. Notice that there is a new entry in the top left window entitled ‘Workspace’. There is now an entry “ans” there of size 1x1. “ans” is a variable. This means that it’s a string of text that has a value (number) assigned to it. To see this, type

ans

at the prompt and then hit enter. As you can see MATLAB again returns ans = 15, i.e. it remembers that ans holds a value of 15. ans is a special name for a variable in MATLAB. It is assigned the value of the answer to the expression that you type at the prompt. In similar manner we can perform other mathematical calculations like addition, subtraction, division etc.

**Creating own variables to store values in Matlab**

You can create your own variables. For example, type in

x=10

Now MATLAB has another entry in the ‘Workspace’ window called x. Now if you type x, MATLAB will know that its value is 10. For example, type

x+5

MATLAB will give you the correct answer 15.
Notice that MATLAB is case sensitive (this is x and X are two different variables).

**Complex numbers**

The instruction

\[ c = \text{complex}(a, b) \]

creates a complex number “c” with real part “a” and imaginary part “b”. An equivalent expression is

\[ c = a + b*\text{i} \quad \text{or} \quad c = a + b*\text{j} \]

All three instructions will generate a complex variable “c” with real part “a” and imaginary part “b”.

The instructions “\text{real}(c)” and “\text{imag}(c)” returns the real and imaginary part of the complex number “c”.

- Absolute value of a complex magnitude: \( \text{abs}(X) \)
  The instruction “\text{abs}(X)” returns an array \( Y \) such that each element of \( Y \) is the absolute value of the corresponding element of \( X \). In the case that \( X \) is complex number, \( \text{abs}(X) \) returns the complex modulus (magnitude). This instruction is equivalent to:

\[ \text{sqrt}(\text{real}(X).^2 + \text{imag}(X).^2) \]

- Phase angle: \( \text{angle}(c) \)

The phase angle of a complex number “c” can be obtained with the instruction

\[ P = \text{angle}(c) \]

For complex \( c \), the magnitude \( R \) and the phase angle are given by

\[ R = \text{abs}(c) \]

\[ \theta = \text{angle}(c) \]

The instruction

\[ c = R.*\text{exp}(i*\theta) \]

converts back to the original complex “c”.

- Complex conjugate
  To obtain the complex conjugate of a complex magnitude “c” the instruction is

\[ Cc = \text{conj}(c) \]
**Matrixes**
To enter a matrix simply type in the command window the matrix elements separated by spaces, and each row separated by “;”. For example we can enter a row vector with the following command

\[ a = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \end{bmatrix} \]

and a column vector with

\[ b = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \end{bmatrix} \]

In the workspace window it will be listed these two variables with the respective assigned values, \( a \) is a matrix with 1 row, and 9 columns; \( b \) is a matrix with 1 column and 9 rows. The operation \( a \ast b \) is a matrix multiplication that will give a 1x1 (scalar) matrix. The operation \( b \ast a \) instead will give as result a 9x9 square matrix. In the example \( S = a \ast b \) gives a number and \( M = b \ast a \) gives a 9x9 square matrix.

MATLAB is specially suited to operate with matrixes. For example we can create a square matrix composing 4 \( M \) matrixes as being blocks. The instruction \( MM = [M \ M; M \ M] \) generates a new 18x18 square matrix where each quadrant is the square matrix \( M \). All operations in MATLAB are understood as matrix operations (for example \( * \) stands for matrix product, \( + \) is matrix addition etc.). However if we want to operate element to element, the instruction is “\( . \ast \)” of “\( . + \)”, this is the operator preceded by period. The instruction \( \text{det}(M) \) will produce the determinant of matrix \( M \). For example

\[ \text{DM} = \text{det}(M) \]

will store the value of the determinant of matrix \( M \) in the variable \( \text{DM} \).

**Matlab as a Mathematical tool**
MATLAB allows you to define (and evaluate) your own functions as well. For example, lets define a function \( f(x) = x^2 + 1 \). To do this, simply type in

\[ f = x.^2 + 1 \]

Suppose \( x \) has a value of 10, the answer is 101. You can now change the value of \( x \). For example, type

\[ x = 5 \]

and enter, then type

\[ f = x.^2 + 1 \]
again. You should now get 26.

However, you don’t want to type the expression for \( f(x) \) every time you want to change the value of \( x \). You might want to define a function \( f(x) \) for a range of values of \( x \). To do this in MATLAB we need to make \( x \) be a range of values. For example, suppose we want to make \( x \) to go from 1 to 10. To do this in MATLAB, you type

\[
x = 1:10
\]

You will get

\[
x = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{pmatrix}
\]
as a result. Now, \( x \) is a list of values from 1 to 10. If we now type

\[
f = x.^2+1
\]

we will get 10 values of \( f \) for each value of \( x \). In other words, we have defined \( f \) as a function of \( x \). Right now the difference between two consecutive values of \( x \) is 1. To change this, we put the step between two consecutive values between the maximum and minimum values. For example type

\[
x=1:0.5:10
\]

You will get

\[
x = \begin{pmatrix} 1.0000 & 1.5000 & 2.0000 & 2.5000 & 3.0000 & 3.5000
4.0000 & 4.5000 & 5.0000 & 5.5000 & 6.0000 & 6.5000 & 7.0000 & 7.5000
8.0000 & 8.5000
9.0000 & 9.5000 & 10.0000 \end{pmatrix}
\]

Now \( x \) still ranges from 1 to 10, but now it takes on 19 values with a step of 0.5. Since we redefined \( x \), we now need to redefine \( f(x) \) as well. This means that we must again type \( f = x.^2+1 \). \( f(x) \) now has 19 values as well.

**Plotting**

To plot \( f \) as a function of \( x \), type \( \text{plot}(x,f) \). A new window will come up with a plot of \( f(x) \) as a function of \( x \). MATLAB has many features for plotting. We will now learn a few of
them. First of all we want to define our axes. This is very simple to do. To define the x-axis, type

xlabel('x')

in the Command window. Now switch to the window with the figure. You will see a label on the x-axis. Let’s do the same for the y axis. Predictably, to do this you need to type

ylabel('f(x)')

Now, if we want to put a title on our graph the command it
title('Function f')

As you can see, a lot of the commands are quite intuitive. Below is a graph for x.^2.

We can also plot in the same graph several functions. For example we have

\[ u = x^2 \]
\[ v = 2x + 10 \]
\[ w = 3x^2 - 100 \]

and x ranges from 1:20. In Matlab we will write these as
Fone = x.^2
Ftwo = 2.*x + 10
Fthree = 3.*x.^2 - 100

Use following command
plot( x,Fone,x,Ftwo,x,Fthree)

Solve the following exercises

1- Exercise (25 points)
Find the Cartesian representation for the following complex numbers and calculate the modulus

- \( Z_1 = \sqrt{3} e^{i\pi/4} \)
- \( Z_2 = 2 e^{i\pi/6} \)
- \( Z_3 = \sqrt{3} e^{3i\pi/4} \)
- \( Z_4 = 2 e^{i\pi} \)
- \( Z_5 = 2 e^{-i\pi} \)
2- Exercise (25 points)

a) Consider the complex number $Z = 2 + j0.2$. Plot in the complex plane $Z, Z^2, Z^3$ and $Z^{1/2}$.

3- Exercise (25 points)
Find the highest and lowest temperatures in Fort Collins during last December (you can find this information for example in http://www.weather.com/), and plot them in a single graph.

4- Exercise (25 points)
Enter the following matrixes:

\[
A = \begin{pmatrix}
1 & 0 & 8 \\
7 & 9 & -8 \\
-6 & 5 & 4 \\
\end{pmatrix}
\quad B = \begin{pmatrix}
1 & 2 & 3 \\
4 & -5 & 6 \\
7 & 8 & 8 \\
\end{pmatrix}
\quad C = \begin{pmatrix}
7 & 9 & 7 \\
6 & 5 & 8 \\
7 & -6 & 5 \\
\end{pmatrix}
\]

Check the following rules of linear algebra:

- a- Is matrix addition commutative? Compute $A+B$ and compare with $B+A$
- b- Is matrix addition associative? Compute $(A+B)+C$ and compare with $A+(B+C)$
- c- Is multiplication with a scalar distributive? Compute $3*(A+B)$ and compare with $3*A+3*B$
- d- Is multiplication with a matrix distributive? Compute $A*(B+C)$ and compare with $A*B+A*C$
Experiment #2  
Basic use of MATLAB® (2)

Objective: You will be introduced to basic use of MATLAB

Loops
It is possible to generate loops with MATLAB like in most computer languages. We will review here the “for” loop. The instruction “for” repeats statements a specific number of times indicated in the index. Loop counter is initialized to the indicated initial value at the start of the first pass through the loop, and automatically increments by 1 each time through the loop until the final value is reached. The syntax is:

\[
\text{for } x=\text{in:step:end, statements, end}
\]

Example:
\[
\text{for } i=1:100 \\
\quad x(i)=i \\
\text{end}
\]
will store in the vector x the first 100 numbers. The step (default) in this case is “1”. It is possible to indicate another step size different than 1.

Example:
\[
\text{for } i=1:2:100 \\
\quad x(i)=i \\
\text{end}
\]
Will fill a vector x with the index values in the odd places. Writing so many instructions sometimes can be inconvenient, especially if you have to iterate the calculation. To solve this problem it is possible to write a series of instructions in a text file (with extension .m). These “m files” will allow you to easily repeat a series of instructions without necessity to type them over every time. To generate the “m file” in the “COMMAND” window type “edit”. This will open another window, the “EDITOR” window where you can type the series of instructions.

Type in the editor window the series of instructions. For example

\[
\text{for } i=1:20 \\
\quad x(i)=i^2 \\
\text{end}
\]
will generate a vector x with the squares of 1 to 20.
Save the m file using the “save” instruction in the editor window. Typing the name of the m file in the command window will make MATLAB to execute the list of instructions listed in the m file.
Now if for example you want to calculate the squares of numbers from 1 to 40 (instead of 20), you will not need to re-type all the instructions, just change the limit in the .m file and operate again.
Editing m files is a very convenient way to run a given program changing parameters without the necessity to type all the instructions every time.

**Cramer’s rule review.**
One possible way to solve an equation system is using Cramer’s rule. Given for example a set of 3 linear equations

\[
\begin{align*}
ax + by + cz &= d_1 \\
ax + by + cz &= d_2 \\
ax + by + cz &= d_3
\end{align*}
\]

can be written as

\[
\begin{pmatrix}
a_1 & b_1 & c_1 \\
a_2 & b_2 & c_2 \\
a_3 & b_3 & c_3
\end{pmatrix}
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
=
\begin{pmatrix}
d_1 \\
d_2 \\
d_3
\end{pmatrix}
\]

Using Cramer’s rule the solutions can be obtained by

\[
\begin{align*}
x &= \frac{d_1 b_2 c_3 - d_2 b_1 c_3 - d_3 b_1 c_2}{a_1 b_2 c_3 - a_2 b_1 c_3 - a_3 b_1 c_2} \\
y &= \frac{a_1 d_2 c_3 - d_1 b_2 c_3 - d_3 b_2 c_1}{a_1 b_2 c_3 - a_2 b_1 c_3 - a_3 b_1 c_2} \\
z &= \frac{a_1 b_2 d_3 - d_1 b_2 c_3 - d_2 b_1 d_3}{a_1 b_2 c_3 - a_2 b_1 c_3 - a_3 b_1 c_2}
\end{align*}
\]

In general, for a set of N equations

\[
\begin{pmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{nn}
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n
\end{pmatrix}
=
\begin{pmatrix}
d_1 \\
d_2 \\
\vdots \\
d_n
\end{pmatrix}
\]

The solutions can be obtained evaluating the following determinant ratios:

\[
x_k = \frac{D_k}{D}\quad \text{where}
\]
Plotting in 2 dimensions
We will review the basic instructions to plot
Suppose you have an array as shown below:
x = 1:10
It will print the following
x =
  1   2   3   4   5   6   7   8   9   10
If you have another variable say Y which is the square of each term in array in X it will be:
Y = x. ^2
y =
  1   4   9   16  25  36  49  64  81  100
The following ways you can give your command to plot x,y
Example:
plot (x,y) is going to produce the figure shown below

It is possible to indicate MATLAB the symbols we want in our plot. For example the instruction

plot (x,y, '*')

is going to produce the figure shown below with star shaped points
Or we can indicate to plot the data points with circles in color blue adding ‘bo’

plot (x,y,’bo’)

Or red dots adding ‘.r’

plot (x,y,’.r’)
To make your plots more descriptive and explanatory you should add labels, titles and legends if necessary.
Taking the previous example of x and y. If we write the following statements, you get the following explanatory plot shown below.

```
plot(x,y,'b')
xlabel('x axis')
ylabel('y axis')
title('Square Values')
```

**Exercise (20 points)**
Use the editor window to create a m file. In this file write a series of MATLAB instructions using the “for” instruction to create

a- A vector A whose elements are the log of the first 10 numbers
b- A vector B whose elements are the first 10 odd numbers
c- A vector C whose elements are the square roots of the first 10 even numbers
d- Plot all vectors in separate plots

e- Plot all vectors in a single plot. Use different markers for the different vectors

**Exercise (20 points)**
Write a MATLAB code to compute and plot the complex number $e^{i\theta}$ for $\theta = \frac{2\pi i}{360}$ and $i = 1, 2, K, 360$

**Exercise (20 points)**
Using two “nested” loops, write a MATLAB code that will produce a 10×10 matrix where each element equals to the sum of the element’s indices.

**Exercise (20 points)**
Find the solutions for the following equation system using the Cramer’s rule.

\[
\begin{align*}
x + 6y - 12z + 3w &= -20 \\
x - 3y &= 12 \\
-3x - 14y + 10w &= 0 \\
6x + 3y + 5z + 5w &= 15
\end{align*}
\]

**Exercise (20 points)**
Repeat the former exercise writing the equation system as a product of matrixes

\[A * X = B\]

where A is the coefficients matrix, X is the column matrix of variables and B is the independent terms column matrix. Solve the equation system by solving the matrix equation

\[X = A^{-1} * B\]
Experiment #3
Introduction to Laboratory Equipment

Objective: In this lab you will be introduced to basic laboratory equipment that you will use in the rest of the course. You will also explore the behavior of simple DC circuits.

* Methodology:

This lab involves measuring voltage and current and performing calculations. You are expected to show your results and work in this packet or also attach additional pages.

* General Procedures: Please read before you start working

- You must take good care of the equipment and follow basic safety rules in order to maintain the equipment in good working conditions, and to prevent accidents.
- Always check connections before applying power to any circuit or device. You do not want to exceed the power limitations of the device or otherwise it will be damaged.
- When using the multimeter and you are not sure of the approximate values you will be measuring start by selecting the least sensitive scale setting then slowly work your way down.
- Disconnect power supplies (current and voltage sources) from a circuit before measuring resistance as multimeters use internal power sources when measuring resistances.
- Switch the power supply off when making adjustments in your circuit connections or when adding new components to avoid short circuit.

* Equipment list:

You will use the acquisition portable device Xplorer GLX® from Pasco. This is a handset with multiple functions capable to acquire digital signals from a variety of detectors available in the laboratory. Read carefully the quick guide to be familiar with the multiple functions of the device.

Be aware of the voltage/current limits of the device you are using consulting the User’s Guide. Voltage probes are designed to measure voltages between +10V and -10V.

If you are not sure about the characteristics of the equipment a complete user guide can be found in: 

Take the following precautions:

- DO NOT EXCEED THE MAXIMUM VOLTAGE OR YOU CAN DAMAGE PERMANENTLY THE Xplorer.
- Resistors can get very hot when connected in a circuit. Do not touch the resistors when the circuit is closed.
• **Basic Circuit Elements:**

The figure below shows the symbols of the simplest circuit elements that you will use in the different laboratories during the semester.

![Circuit Elements Diagram](image)

• **Resistor Color Bands:**

Carbon resistors are the most common ones, and come in a wide range of power ratings. Their resistances are identified by a color code. In addition to the resistance value, a tolerance value is included in the code. Typically carbon resistors employ 5% tolerances, and can handle \( \frac{1}{4} \) W. This means that the current and voltage have to be controlled not to exceed the power ratings.

On each resistor you will find 3 or 4 color bands, each color represents a number, the colors which you are going to see are :-

![Resistor Color Band Diagram](image)
Color | Represents
---|---
Black | 0
Brown | 1
Red | 2
Orange | 3
Yellow | 4
Green | 5
Blue | 6
Violet | 7
Gray | 8
White | 9
Silver | 10% tolerance
Gold | 5% tolerance
No 4th band | 20% tolerance

Usually the first band is positioned closer to the lead. For more information refer to the textbook or the class notes (in the course website).

**Example :-**

<table>
<thead>
<tr>
<th>1st band</th>
<th>2nd band</th>
<th>3rd band ( # of 0 )</th>
<th>4th band (Tol.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td><strong>Black</strong></td>
<td>Black</td>
<td>No band</td>
</tr>
<tr>
<td>Brown</td>
<td>Brown</td>
<td>Brown</td>
<td><strong>Gold</strong></td>
</tr>
<tr>
<td>Red</td>
<td>Red</td>
<td><strong>Red</strong></td>
<td>Silver</td>
</tr>
<tr>
<td>Orange</td>
<td>Orange</td>
<td>Orange</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
<td></td>
</tr>
<tr>
<td>Violet</td>
<td>Violet</td>
<td>Violet</td>
<td></td>
</tr>
<tr>
<td>Gray</td>
<td>Gray</td>
<td>Gray</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>White</td>
<td>White</td>
<td></td>
</tr>
</tbody>
</table>

Consider a resistor that have the color bands shown in (bold/italic) in the table above,

The first band (brown) = 1
The second band (black) = 0
The third band (red) (# of 0) = 2
The forth band (Tol.) = 5%

Then the value of the resistor from left to right will be :-

1(brown) , 0 (black) , **00** (red) , +/- 5% (gold ) = **1000 +/- 50** ohms
**Practice I (10 points):**

Now, write the value of each resistor according to the color code arrangement that is shown below,

<table>
<thead>
<tr>
<th>1st band</th>
<th>2nd band</th>
<th>3rd band</th>
<th>4th band</th>
<th>Resistance +/- Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange</td>
<td>Orange</td>
<td>Red</td>
<td>Silver</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>Blue</td>
<td>Red</td>
<td>No band</td>
<td></td>
</tr>
<tr>
<td>Brown</td>
<td>Black</td>
<td>Orange</td>
<td>Gold</td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>Brown</td>
<td>Brown</td>
<td>No band</td>
<td></td>
</tr>
</tbody>
</table>

- **Voltage/current sensors and Power Supplies:**

1.) Obtain a set of 3 resistors with values between R=10Ω and R=60Ω

   ✓ Using the color code find the nominal value of the three resistors
   ✓ Now check the value of your resistor using the ohmmeter by connecting the 2 terminals of the resistor to the 2 leads of the ohmmeter. Make sure the resistance function is selected on the meter.

Complete the following table

<table>
<thead>
<tr>
<th>Resistor</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal value</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured value</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- How much of a difference is there between the ideal and true resistance values? Does this fit in the acceptable tolerance limits?

2.) Build the circuit shown below using resistor #1. Connect a power supply to the circuit. Your lab instructor will demonstrate the proper use of power supplies. Before starting to work, be familiar with the control panel of the power supply. You are going to measure the current through the resistor and the voltage drop across the resistor. The Xplorer GLX handset is compatible with the voltage/current sensors available in the lab. Connect the voltage probe to the Xplorer handset. Set up a simple circuit as suggested in the scheme below. Your circuit should look like the picture.
Connect the voltage ($V_m$) and current ($I_m$) sensors to the circuit. How should they be connected? Remember to refer the negative terminal of the source to ground. Consult with the TA if you have doubts.

Complete the connections with the voltage source OFF. After checking the connections, make sure that the settings in the voltage source are below the maximum allowed limit (10 V). Your circuit should look like the picture above.

Utilize the +/- 6 V output of the voltage source

Remember, you should always turn off the power to a circuit while modifying it. Afterwards, you will need to turn the power back on to make the measurement. The best way to turn the power on and off to the circuit is to use the “Output On/Off” button on the power supply. This allows the voltage and current settings to remain unchanged.

ALTERNATIVE EQUIPMENT: PROTOBOARD

If you have available one protoboard you may use it to continue with the experiments. You’ve probably seen electronic circuits assembled on green printed circuit boards with little black plastic integrated circuits having several metal leads soldered to the board. These boards often contain other electronic components, such as resistors. When experimenting with circuits, we typically want to measure or test a new circuit without having to solder the components or design a printed circuit board. White plastic protoboards are very useful in these cases. An example of a circuit on the protoboard is shown in the figure on the next page. Refer to it for the following discussion.

Protoboards have a number of holes that are arranged on a square grid. The wires or leads of components can be inserted in the holes. The electrical components are connected by wires (actually spring clips) that are hidden within the board. These built-in wires are shown in the following diagram as gray lines. To properly connect circuits on the boards, you must understand how the holes are wired together. In the main portions of the board, holes in a horizontal line are all wired together, assuming the board is oriented as shown with the long grooves running vertically. Thus all the holes in a row will have the same potential. If you wish to wire two components together, place one lead of the first component in any hole on the row and a lead of the second component in any other hole on that same row. However, if the leads were placed in different rows
Protoboard: A simple circuit on a protoboard connecting a resistor across a power supply. The gray lines represent conducting metallic clips that are inside the protoboard. The metallic clips electrically connect adjacent holes either horizontally or vertically depending on where they are located. Plugging two wires into one clip has the same effect as touching the wires together.

they would not be electrically connected by the board. The rows have a gap in the middle that is useful for separating the leads of integrated circuits. On the sides, there are long vertical columns of holes that are connected as indicated by long red and blue lines printed on the board. These are typically used for distributing power and ground connections to your circuit components as shown in the next page.

**Practice II (20 points)**

- Using your circuit solving knowledge, what value of \( V_m \) do you expect across the resistor?

  a- Set the voltage in this source to 1 V, measure the voltage indicated by the voltage sensor and the current.
  b- Increase the voltage in the source in steps of 1 V up to a maximum voltage of 6 V
  c- Change to resistor #2 and repeat the measurements indicated in a) and b).
  d- Complete the following table

<table>
<thead>
<tr>
<th>( R#1 )</th>
<th>( R#2 )</th>
<th>( R#3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_m ) [V]</td>
<td>( I_m ) [A]</td>
<td>( V_m ) [V]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Practice III (10 points)

Plot the data for the three resistors in the same graph using MATLAB. From the graph determine the best fit and the value of the resistance in each case. How this value compares with the nominal value?

<table>
<thead>
<tr>
<th></th>
<th>Resistor #1</th>
<th>Resistor #2</th>
<th>Resistor #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
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<td></td>
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<tr>
<td>from the</td>
<td></td>
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<td></td>
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<tr>
<td>graph</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Practice IV (10 points)

Now that you know V and I in the circuit, find R using Ohm’s law: V = IR. How does this resistance value compare with the color band method and the value you measured using the ohmmeter?

<table>
<thead>
<tr>
<th>Color band method</th>
<th>Ohmmeter method</th>
<th>Ohm’s law: V = IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal value</td>
<td>Measured value</td>
<td>Calculated value</td>
</tr>
</tbody>
</table>

Comment on your results:-
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Page 7 from 7
**Experiment #4**

**Current-Voltage Characteristics of Resistors and Diodes**

**Objective:** In this lab you will measure and plot the current-voltage (I-V) characteristics of two common circuit elements, resistors and diodes.

* Part (I)  I-V characteristics of resistors (50 points):

1.) Select a new resistor with a value between $R=10\,\Omega$ and $R=60\,\Omega$. Set a circuit and the corresponding measuring instruments to record simultaneously the voltage $V_m$ across the resistor and the current $I_m$ through the circuit. The voltage source that you will use in this experiment is the output signal from the function generator.

![Circuit Diagram]

* Measurements using the function generator:

A function generator is a source that allows to generate time-varying signals with different temporal shapes (saw-tooth, sinusoidal, square, etc.). Utilize the function generator to power your circuit. The EXPLORER handset has the possibility to record time-varying signals and store them in a file that you will be able to download using the UBS interface.

A quick guide how to use the XPLORER handset can be found in:


- Follow the same safety rules as described before in the experiment 2. Do not exceed the maximum allowable voltage.
- Bring a USB flash drive memory to transfer the data files from the XPLORER handset to the computer.

Before recording the signal you must initialize your device and set the acquisition parameters.
- Connect a V-I sensor in the Xplorer.
- Set the sampling rate. Navigate the handset menu to

“sensors” >> “sample rate” >> 100 samples/sec
• Set the graphic mode in the handset:

“graph” >> “graph” >> “two graphs”

Now the handset is ready to acquire the V-I signals from the sensor. Set the frequency in the function generator to a convenient value. Discuss with the TA the possibilities. Record in the Xplorer handset both the voltage Vm and the current Im.

Activate the handset to acquire the data from the circuit. (To avoid generating a huge datafile, record data for short period of time, 2-3 seconds approximately). You will see in the LC display the two graphs showing the voltage and the current in the resistor as a function of time.

• Connect the USB flash memory to the USB port in the handset
• Navigate the handset menu from “home”:

“table menu” >> “Table (F4)” >> “Export Data”

• Select the device (USB drive), label the file, press OK (F1)

The file will be transferred to the USB flash memory. Use the flash memory to transfer the data to the computer and analyze them using MATLAB

• Using MATLAB plot Im vs Vm
• Attach the plot to your report.

- The relationship between voltage and current, which is given by the equation V=IR, is linear. After plotting Im vs Vm, determine the slope. What does the slope mean in terms of Ohm’s law? Is it what you expect?

Using the data you collected for I and V in the resistors, calculate the power, P, dissipated in the resistors using the formula you’ve learned in class. Plot P vs I and P vs V for both resistors in MATLAB and attach the plots to your report.

- What is the relationship between P and I (for example, is it linear)?

- What is the relationship between P and V?
* Part (II) I-V Characteristics Diodes (50 points):

- **Diodes - The Simplest Semiconductor Device**

A diode is a two terminal circuit element that has a high resistance to current in one direction and a low resistance to current in the other direction. A diode can be thought of as an electrically controlled switch. It acts as a one-way valve for electrons. The two ends of the diode are called the anode and the cathode. Current flows easily from anode to cathode, but not the other way. Note that the diode’s behavior depends on the polarity of the current. This is not true for resistors. Thus you can swap the leads of a resistor in a circuit without causing any changes, but doing so with the diode can cause the circuit to fail or worse, damage components and equipment. The cathode end of a physical diode is indicated by a band around the diode near the cathode lead.

- Construct the circuit shown below and set the power function generator to deliver 5V peak to peak and a sinusoidal wave function.

- Record the voltage across the diode ($V_d$) and the current through the circuit ($I_d$) using the Xplorer handset and the V-I measuring unit in a similar way as you did for the resistor

- Record several set of data changing the settings of the function generator to produce different functions (sinusoidal, saw tooth, square) and varying the offset in the function generator

- Plot the Current $I_d$ (y axis) vs. the Voltage $V_d$ (x axis) in the hand set.

- Retrieve the file form using the USB port and download the data in the computer
• Using MATLAB plot Id vs Vd

• Attach the plot to your report.

Describe the waves that you recorded and compare them with the wave delivered by the function generator.

From the plots that you obtained, can you calculate the resistance of the diode?

At what value of $V_d$ does it appear that the switch turns on? How much maximum current did you measure?

$V_D$ to turn on switch = ............................

$I_{Max} = ..............................$

- Is the relationship between $I_D$ and $V_D$ linear for the entire measurement range?
  ............................................................................................................................
  ............................................................................................................................
**Experiment #5**  
*Series and Parallel Resistor Circuits*

**Objective:** You will become familiar with the MB Board and learn how to build simple DC circuits. This will introduce you to series and parallel circuits

* **Equipment list:**
  1. A MR magnetic board
  2. A set of components

In this experiment you will use a magnetic board that allows making interconnections with different components in a simple way, without soldering. First identify the two boards of the set, one circuit board and one component panel. The power supply will be a 9 V battery that is connected in the top right corner of the circuit board. The small power board has a switch, a connector to plug the 9 V battery, a resistor that limits the current, and a red LED that indicates that the supply is ON. This small power board feeds the red columns indicated with the symbol + (plus sign) with +9V and grounds the black columns indicated with the symbol – (minus sign).

**ALTERNATIVE:** You may use the PROTOBOARD described in Experiment 3 in this lab. Either (PROTOBOARD or MB Board) are acceptable to complete this experiment.

**(I). Resistors in series (30 points)**

**Procedure:**

1.) Construct three serial circuit using the available resistances, 100Ω, 1kΩ, 10kΩ, 100kΩ in the component’s board. Measure for each circuit the equivalent resistance Req, the voltage drop in each resistance (V₁ and V₂), the voltage across the series (V₁+V₂) and the current in the circuit (I).
2.) Compare the measured values with the calculation using basic circuit analysis.

3.) Calculate the total voltage drop across the resistors and enter it in the table in the column for \( V_{1} + V_{2} \). The equivalent resistance of the series resistor combination is the value of a single resistor that could replace the two resistors and result in the same total voltage and current.

4.) Answer the following questions:

a) What is the relationship between the voltage across the resistors and the resistor value? Explain

b) Is the current through both resistors (R1 and R2) the same? Why?

c) Are your measured and calculated values for \( R_{eq} \) slightly different? Explain observed or potential sources of discrepancy.

- **Comment on your results:**

<table>
<thead>
<tr>
<th>R1(Ω)</th>
<th>R2(Ω)</th>
<th>Measured Req (Ω)</th>
<th>( V_{1} ) (V)</th>
<th>( V_{2} ) (V)</th>
<th>( V_{1} + V_{2} ) (V)</th>
<th>I (mA)</th>
<th>Calculated Req (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>100</td>
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<td>1000</td>
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<tr>
<td>10000</td>
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</table>

Tips to build your series resistor circuit:
a- Use the components in the component’s board to build you series circuit. To help in the design, you may want to use the figure below to sketch the circuit that you will build.

b- To measure simultaneously the current and the voltage, use the V-I sensor and the Xplore handset that you used in experiments 2 and 3. In the component board you have 4 free sockets that you can use to inset your voltage and current probes.

c- To make connections between the different components, use the jumpers (blue components labeled 2 holes, 3 holes….)

d- How should the voltage probe be connected (in series or in parallel with the resistors)?

e- How should the current probe be connected (in series or in parallel with the resistors)?

Discuss with the TA if you have doubts before activating the power supply.

(II). Resistors in parallel (30 points)

1.) Construct two parallel circuit with the available resistors in the component’s board.

<table>
<thead>
<tr>
<th>R1(Ω)</th>
<th>R2(Ω)</th>
<th>Measured Req (Ω)</th>
<th>I1 (mA)</th>
<th>I2 (mA)</th>
<th>I1 + I2 (mA)</th>
<th>V1 (V)</th>
<th>Calculated Req (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1000</td>
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<tr>
<td>1000</td>
<td>10000</td>
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</tbody>
</table>

2.) Measure the equivalent resistance of the parallel set, the currents through each resistor I1 and I2, the total current in the circuit and the voltage across the resistances.
3.) Using the values for $R_1$ and $V$ calculate the value of the current, $I_1$, flowing through resistor $R_1$. Repeat this calculation for the current, $I_2$, flowing through resistor $R_2$ using the values for $R_2$ and $V$.

4.) Calculate the total current provided to the combined resistors and enter it on the table in the column for $I_1 + I_2$. The equivalent resistance of the parallel resistor combination is the value of a single resistor that could replace the two resistors and result in the same voltage and total current. The equivalent resistor value can be calculated simply from Ohm’s law as $R_{eq} = V/(I_1 + I_2)$. Enter the calculated equivalent resistance in the final column of the table.

5.) Answer the following questions:

a) Is the voltage the same across each resistor? Explain.

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b) Is the current through both resistors ($R_1$ and $R_2$) the same? Which one is larger? Why?

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c) Are your measured and calculated values for $R_{eq}$ slightly different? Explain the observed or potential sources of discrepancy.

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- **Comment on your results:-**

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- **III- Circuit with a potentiometer**
1. Construct a serial circuit using a potentiometer (100kΩ) and a 100kΩ resistor from the component’s board. Measure the voltage drop in the potentiometer and in the resistance ($V_P$ and $V_R$), the voltage across the series ($V_P + V_R$) and the current in the circuit ($I$).

Sketch your circuit in an auxiliary piece of paper and lay out the circuit in the following figure.

2. Vary the value of $R_P$ and complete the following table. Make a set of data with values between the maximum and minimum value of $R_P$.

<table>
<thead>
<tr>
<th>$R_P$ (Ω)</th>
<th>Measured Req (Ω)</th>
<th>$V_P$ (V)</th>
<th>$V_R + V_P$ (V)</th>
<th>$I$ (mA)</th>
<th>Calculated Req (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

**IV. Circuit Design (40 points):**
A.) Voltage divider circuit design :-

In this section, you will design a voltage divider circuit and understand some of the practical limitations of this circuit. A voltage divider can be used to provide a new voltage by reducing or dividing the voltage available from a battery or fixed voltage supply. The battery in the circuit board supplies 9 V and is your fixed voltage supply.

Design your voltage divider circuit by choosing \( R_1 \) and \( R_2 \) so that the following criteria are met:

- The output voltage should be \( V_{OUT} = 0.09 \) V.
- The total current drawn from the power supply should be < 10 mA.
- The resistors need to be available from the component’s board.

Sketch your circuit in an auxiliary piece of paper and lay out the circuit in the following figure:

![Circuit Board Image]

1.) Write equations for \( R_1 \) and \( R_2 \) based on these requirements and show your solution:
Design choices: $R_1 = \ldots \Omega$, $R_2 = \ldots \Omega$.

2.) Construct the circuit that you designed using your design values of $R_1$ and $R_2$ from step 1, then measure the following:

$V_{\text{OUT}} = \ldots \ldots \ldots \ldots$  

$I_T (\text{The total measured current}) = \ldots \ldots \ldots \ldots$

- Were the design criteria met? $\ldots \ldots \ldots \ldots$  

B.) Current divider circuit design :-

Design a current divider circuit by choosing $R_1$ and $R_2$ so that the following criteria are met:

- The total current drawn from the power supply must $< 10$ mA.
- The current between $R_1$ and $R_2$ is equally split, $I_1 = I_2$.

Sketch your circuit in an auxiliary piece of paper and lay out the circuit in the following figure.
1.) Write equations for R1 and R2 based on these requirements and show your solution:

**Design choices:** R1 = ………………Ω, R2 = ……………… Ω.

2.) Construct the circuit using your design values of R1 and R2 from step 1, then measure the following:

I1 =……………………....

I2 =……………………....

I_T (The total current drawn from the power supply) = ………………………....

- Were the design criteria met? ………………………....
Experiment #6

Thevenin Equivalent Circuits and Power Transfer

**Objective:** In this lab you will confirm the equivalence between a complicated resistor circuit and its Thevenin equivalent. You will also learn about matching loads to maximize power transfer.

*Equipment list:*

1. MB Board and components
2. Multimeter
3. Xplorer handset
4. Resistors various values between 100Ω and 5 kΩ.

I.) Thevenin Equivalent (85 points):

Construct the circuit shown in figure 1. Use R1=R4= 10 kΩ and R2=R3=1kΩ. Various values of resistance will be used for R\text{load}. To connect the different loads use the multipurpose socket in the component’s board. In this experiment, we will consider the Thevenin equivalent for the circuit composed of R1, R2, R4, R5 and the 9V source. R\text{load} is the load and is not part of the circuit to be replaced with a Thevenin equivalent circuit. By the way, this configuration is called a bridge circuit.

Install a 100Ω resistor for R\text{load}, then measure the voltage between the points a and b and measure the current I\text{load} which passes through R\text{load}. To perform these measurements use the Xplore handset unit.

- How should the amp meter be connected?
- How should the voltmeter be connected?
Change the value of $R_{\text{load}}$ and complete the table below. Note that $R_{\text{Load}} = \infty \Omega$ is accomplished by leaving an open circuit between point a and b. The current through the infinite load resistance will be 0 mA as already entered for you in the table. For the case of $R_{\text{load}} = 0 \Omega$, put a wire between points a and b for a short circuit. In this case, the voltage between a and b will be 0 V as shown in the table.

<table>
<thead>
<tr>
<th>$R_{\text{load}}$ ($\Omega$)</th>
<th>$I_{\text{load}}$ (mA)</th>
<th>$V_{ab}$ (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>infinite (open circuit = OC)</td>
<td>0</td>
<td>$V_{OC}$</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (short circuit = SC)</td>
<td>$I_{SC}$</td>
<td>0</td>
</tr>
</tbody>
</table>

Using MATLAB plot the data from the table above on a graph of $V_{ab}$ (y-axis) vs. $I_{\text{load}}$ (x-axis) for all values of $R_{\text{load}}$ and attach the plot to this report.

What type of curve fits the data? What is the slope of the plot (include the right units)?

Now disconnect $R_{\text{load}}$ and the power supply from your circuit. Replace the branch of the circuit that had contained the power supply, $V_s$, with a short circuit. Using the ohm meter measure the resistance between the points a and b.

$R_{ab} =$

How does this value of resistance compare numerically to the slope of the plot in step 5?

Now try to decide how to select values for the components of the Thevenin equivalent circuit shown in Figure 1, so that the equivalent circuit will produce the same effect as the original circuit. That is, the two circuits should produce the same values of $V_{ab}$ and $I_{\text{load}}$ for any of the given load resistors. Think about this problem for a few minutes before continuing.
Do you have all the data to sketch the Thevenin’s equivalent circuit?

You only need to determine the two unknown values, $R_{Th}$ and $V_{Th}$, to establish the Thevenin equivalent circuit in Figure 1. Think through the following questions:

Referring to table 1, what is the value of $V_{ab}$ when no load resistor is connected between points a and b, i.e. when $R_{load} = \infty$? 

Now considering the original circuit in Figure 1, how is $V_{Th}$ related to this value of $V_{ab}$ when no load resistor is connected between points a and b, i.e. when the load is open circuited? 

You’ve just used one of the data points from table 1, the open circuit point, to figure out one of the unknown values of the Thevenin equivalent circuit, $V_{Th}$. Now let’s use another data point to figure out the other unknown value, $R_{Th}$. Determining $R_{Th}$ turns out to be simplest if we now consider the short circuit data point. Again looking at Figure 1, how much current will flow between points a and b if we short circuit them, i.e. if $R_{load} = 0 \ \Omega$?

Solve this relationship for $R_{Th}$ and use numerical values for the short circuit current from Table 1 to determine the value of $R_{Th}$.

Record your values for the Thevenin equivalent circuit elements below:

$V_{Th} =$ ..................................  $R_{Th} =$ ..................................

Draw the schematic of your Thevenin equivalent for the original circuit. It should be in the form of one resistor ($R_{Th}$) and a voltage source ($V_{Th}$). Locate the points a and b in your new schematic.
Connect the circuit using component values you have calculated and reconnect $R_{\text{load}}$ between the points a and b. Your new circuit should look like the circuit in figure above.

To adjust the value of the equivalent Thevenin voltage, use a variable DC power supply and connect to the board of the MB circuit board using alligator clips.

Measure the voltage between the points a and b and measure the current $I_{\text{load}}$ which passes through $R_{\text{load}}$ utilizing the same set up as you used with the original circuit. Record the values of the current $I_{\text{load}}$ and the voltage $V_{\text{ab}}$ for different load resistors and fill the following table.

<table>
<thead>
<tr>
<th>$R_{\text{load}}$ (Ω)</th>
<th>$I_{\text{load}}$ (mA)</th>
<th>$V_{\text{ab}}$ (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>infinite (open circuit = OC)</td>
<td>0</td>
<td>$V_{\text{OC}}$ :</td>
</tr>
<tr>
<td>0 (short circuit = SC)</td>
<td>$I_{\text{SC}}$ :</td>
<td>0</td>
</tr>
</tbody>
</table>

Now using MATLAB plot the data from the table above on a graph of $V_{\text{ab}}$ (y-axis) vs. $I_{\text{load}}$ (x-axis) for all the values of $R_{\text{load}}$ and attach the plot to this report. It is best if you can plot this data and the data from your data of the original circuit on the same axes, i.e. two curves on the same graph. Don’t forget to use a legend or another method to indicate which curve is which.

How do the two set of data from compare? Are the two circuits equivalent? Comment on the differences.

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Page 4 of 5 01/07/15
II.) Load Matching for Maximum Power Transfer (15 points):

Using the data from Table 2, calculate the power delivered to the load resistor for each value of R\(_{\text{load}}\), and enter the data below.

**Table (3)**

<table>
<thead>
<tr>
<th>R(_{\text{load}}) (Ω)</th>
<th>P(_L) (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>infinite</td>
<td></td>
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<tr>
<td>0</td>
<td></td>
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</tbody>
</table>

Now plot this data from Table 3 on a graph of P\(_L\) (y-axis) vs. R\(_{\text{load}}\) (x-axis).

From your plot, what value of R\(_{\text{load}}\) gets the most power?

R\(_{\text{load}}\), max power = .................

How is this value of load resistance related to the resistance values in the original circuit or the Thevenin equivalent circuit?

………………………………………………………………………………………………………

If you wanted to make a single type of measurement for each resistance value to verify the power transfer was maximized, what could you measure? Hint: Don’t just think about electrical measurements only.

………………………………………………………………………………………………………

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Experiment #7

Measurements using Oscilloscope and function Generators

**Objective:** Learn how to use the Function Generator and how measure AC signals with the Oscilloscope and Multimeter.

*Equipment list:

1. Wires
2. Oscilloscope
3. Function Generator
4. Oscilloscope probes
5. BNC to banana adapters

**Introduction:**

The oscilloscope: The oscilloscope (or “scope”) is one of the most common and useful measuring instruments. It is a device that displays time-dependent electrical signals on a screen of a cathode ray tube. The operation of the oscilloscope can be thought imagining a bright spot in a screen, whose position is determined by two voltage signals. Changing the voltage in the vertical signal moves the spot up and down. Changing the voltage in the horizontal signal moves the spot from side to side on the screen.
Originally scopes were made from a cathode ray tube (similar to standard TV sets) with four deflecting plates. The voltage between opposite pairs of plates move the electron beam (that produces the bright spot in the screen) up and down or sideways. Modern oscilloscopes mimic this function using computer screens, microprocessors and analog to digital (A/D) converters instead deflection plates. They also have a number of other interesting features to simplify or automate their operation.

There are two basic modes of operation for the oscilloscope: the SWEEP mode and the X-Y mode.

A) SWEEP mode

This is the most common configuration. In this mode the scope displays a voltage signal in the vertical direction versus time on the horizontal axis. To accomplish this, the signal to be observed is connected to one of the vertical inputs (CHANNEL 1 or 2). The oscilloscope internally generates a horizontal signal using its “time base” circuit that is proportional to time. This signal sweeps the spot from left to right at a constant rate determined by the Time/Div setting in the horizontal control. When the displayed spot reaches the right hand side of the screen, the spot is rapidly repositioned to the left side of the screen. The combined effect of vertical and horizontal movement of the spot created in the screen a display of the vertical signals vs time. For example a sinusoidal varying input voltage will trace a sine or cosine in the screen as shown in the picture above.

One detail that has to be addressed is when to start the display spot moving from left to right. For example with a sinusoidal input signal, if we start the display just as the input signal goes from negative voltage to zero volts, the displayed signal will show the spot rising above zero so that it appears to be a sine wave. If with the same signal we select to start the display when the signal just reached its maximum value and starts to decline, the display will show a cosine. If we start the display in some other arbitrary point, without regard to the value of the input signal we will trace a different curve every time and the display will appear to be constantly changing. To make sure that always we start the display of the signal at the correct time we rely on the idea of triggering. The trigger will determine in the scope when to start the display of the signal sweeping the spot horizontally.
Typically the scope is triggered by comparing the input signal to a fixed reference level, and when the input signal crosses that level, the scope starts the display (horizontal sweep), this tracing out the curve. This comparison with a reference level gives the “trigger level” that can be adjusted. Also necessary is to determine the slope of the signal. For example in a sinusoidal signal, we can set the trigger level when the signal crosses zero, but to uniquely determine the trigger position we have to select the slope (positive if the signal goes from negative values to positive values and negative slope in the signal is decreasing from positive voltage values to negative voltages).

Since oscilloscopes usually have more than one channel to display signals, we should indicate which one has to be used for triggering. This is the “Trigger Source”, That can be channel 1 or channel 2 (for this particular scope). Other triggers sources are “Line” which automatically will trigger the horizontal sweep at a fixed frequency of 60 Hz (line frequency), or “External” which refers the comparison of the reference level to an external signal connected to the external trigger input.

The last detail about triggering is the “Triggering Mode”. The mode described above corresponds to the “Normal Mode”. The scope will trigger only if the signal crosses the reference level with the assigned slope. However that can be annoying since the oscilloscope will not display the signal at all if it never crosses the reference trigger level. All you will see is a blank screen if the triggering level is not correctly adjusted (or a frozen copy of the last triggered sweep in the HP54600 series scope). to rectify this problem, there is another triggering mode called “Automatic”. In “Automatic” the scope will trigger anyway probably displaying an unstable signal. You can then adjust the trigger level to until the input signal crosses it and a stable trace is obtained.

B) X-Y mode

This is a much less common configuration. It does not involve triggering and produces interesting displays for certain applications. In this mode the time base used to control the horizontal position in the sweep mode is turned off. Now both the horizontal and the vertical positions in the display are controlled by the input signals. The X signals is connected to channel 1 and the Y signal to channel 2. If the frequencies of both signals are a multiple of a common base frequency, the display will show a so called Lissajou figure. In the simplest case, where the frequencies of the horizontal and vertical signals are the same, an ellipse is displayed. In this case the ellipticity and orientation of the major axis are related to the phase angle between the two signals and
their relative amplitudes. In no signal is applied to either channel, the trace appears as a dot centered in the scope screen.

Other controls:
VERTICAL Volts/Div: Changes the vertical size of the displayed signal

VERTICAL POSITION. Moves the trace up and down on the screen

VERTICAL 1- Brings up a soft key menu that allows to turn channel 1 on or off or change some of its attributes. VERTICAL 2 does the same for channel 2.

HORIZONTAL Time/Div- Changes the time scale displayed in the horizontal sweep

HORIZONTAL DELAY- This moves the signal from left to right in the screen

AUTOSCALE- Automatically adjust al the controls to display the signal in the input. While usually does a good job, sometimes it is necessary to manually adjust the settings to properly display the signal.

Other features are activated when you press different buttons. Next figure shows the different menus available by pressing different keys on the front panel.
Proper Oscilloscope Use

(This section contains advanced information that you should skip now and refer back to as the need arises in future AC experiments.)

The digital oscilloscopes in the laboratory have many nice features, but must be properly used in order to insure accurate measurements.

Before making phase shift measurements, you will want to adjust the 0V reference for both channel 1 and 2 to be in the vertical center of the screen. Using the position knob for each channel, make sure the small ground symbols at the right of the screen are both exactly centered. You should also make sure you have the correct probe attenuation selected for each channel. It is a good idea to verify the calibration of each channel and the probe by attaching one probe at a time to the small metal test point on the oscilloscope just below the screen. This should produce a clean square wave of the correct amplitude.

When measuring voltages or times on the oscilloscope, expand the scales so that the measured distance covers at least one division and preferably more. Voltage measurements on the oscilloscope are most accurate if the signals fill at least 50% of the vertical extent of the screen. The voltage and time cursors are quite useful for measuring the difference in two voltages or two times. You select this feature with the CURSOR button. When measuring time differences be sure to be systematic and always keep the same cursor, e.g. t1, on the same signal, e.g. V1. In this way you will be able to determine if the phase difference changes sign.

When working with two oscilloscope probes, or sometimes even one, it is very important to properly ground the probes. The black alligator clip should always be connected to the ground point of your circuit which in turn should be connected to the ground point on the waveform generator. Placing the ground clips for the two oscilloscope channels in different locations on the circuit will short out the circuit between those two points.

Sometimes it is desirable to measure the voltage between two different points in the circuit, neither of which is grounded. Most oscilloscopes allow this by providing traces of the sum or difference between two probe voltages measured on separate channels. Use the +/- key between the two channels followed by the appropriate soft keys to select this feature. An apparent “feature” of the oscilloscopes in C107 is that you must have both channels set to the same voltage scale in order for this feature to work correctly. Otherwise, the sum or difference will be incorrectly determined. You may find it useful to turn off one of the channels when doing sum or difference measurements in order to simplify the display. The sum or difference will still be displayed even though one of the channels used for the calculation is not displayed.
The Function Generator:

In previous experiments in this course, you have only used the DC power supply to provide voltages or currents to your circuits. In order to obtain time-varying or AC signals, you will need to use a new instrument, the HP 33120A Function or Waveform Generator. A diagram for the front panel of this instrument is shown below. It is capable of generating a variety of AC functions including sine waves, square waves, triangle waves, and sawtooth waves. Select the desired function using the keys in section 1 of the instrument panel. To change numerical parameters of the signal like frequency or amplitude, press the appropriate key in section 2 and then turn the knob to adjust the value.

When using the function generator in this experiment, you need to make sure that a couple of options are turned off. The first one is modulation. This can be accomplished by power cycling (turning off and on) the function generator to reset its options. Turning off another option, the output impedance correction, is more involved. Pressing Shift and then Enter will access a series of setup menus. Use the right arrow key to select menu D: SYS MENU. Then use the down arrow until “50 OHMS” is displayed. Then press the right arrow key to change the display to “HIGH Z”. Finally, press the Enter key to save this setting. If you fail to change this impedance setting, the function generator will deliver twice the displayed voltage to high impedance devices like the oscilloscope. Further details about operating the instrument can be found in the instrument’s user’s manual.

1-Function /Modulation keys 5-Recall Store state key
2-Menu Operation Keys 6-Enter Number key
3-Waveform modify keys 7-Shift Local key
4-Trigger key 8-Enter Units key
Experiment – Part I
Measuring a Signal From the Function Generator using the Oscilloscope: (45 points)

1- Connecting a signal from the function generator to the oscilloscope:

a. Select a sinusoidal signal with an amplitude of 5V by pressing the key labeled “Ampl” and turning the dial to 10 Vpp. This means that your waveform is 10 volts from the minimum peak to the maximum peak, and 5 volts from average to peak. Verify that the sinusoid function is selected by pressing the key with the picture of a sine wave.

b. Select the frequency of 5000Hz by pressing the key labeled “Freq” and turning the dial to 5000 Hz.

c. Connect the signal from the HP 33120A function generator into the oscilloscope by first connecting a gray probe cable to channel #1 on the oscilloscope. Place a BNC to banana plug adapter on the output connector of the function generator. Clip the black alligator clip of the oscilloscope probe cable to the black terminal of the banana plug making sure that there is metal-to-metal contact. If those mischievous upper classmen aren’t playing tricks on you, the black terminal should also be next to the tab labeled “GND”. Now insert a wire into the red banana plug terminal and secure it by tightening the red plastic covered nut with your fingers. The metal portion of the wire should touch the metal portion of the banana plug to insure a good connection. Finally, clip the hooked tip of the oscilloscope probe cable on the wire.

d. Press AUTOSCALE on the oscilloscope.

- Which axis is voltage plotted against?
  ............................................. (1 point)

- Which axis is time plotted against?
  ............................................. (1 point)

2- Measuring your signal:

There are several ways to measure characteristics of your signal. Under the measure menu there are three buttons:

- Voltage
- Time
- Cursors

1.) First select the voltage button and you’ll see a menu of soft keys appear at the bottom of the screen. Notice that you can toggle between source 1 and source 2 on the far left of the screen. Your signal is in channel 1, so make sure that source 1 is selected.
Try out the other buttons and record your values for

\[ V_{pp} = \] ............................ (1 point)

\[ V_{avg} = \] ............................ (1 point)

\[ V_{rms} = \] ............................ (1 point)

2.) Now select the Time button and you’ll see a different menu of soft keys appear at the bottom of the screen.

Try out the other buttons and record your values for

\[ Freq = \] ............................ Hz (1 point)

\[ Period = \] ............................ s (1 point)

3.) Now select the Cursors button and you’ll see a different menu of soft keys appear at the bottom of the screen.

a. There are four cursor choices: V1 and V2 are the voltage cursors, and t1 and t2 are the time cursors. Once you select a cursor, use the knob below the cursors key to move them.

b. Use the cursor V1 to measure the amplitude and the t1 and t2 cursor to measure the period of the signals listed in the table. (Try pressing both t1 and t2 together- what happens?

\[ \] ............................ (1 point)

c. If you want to erase you cursor readings, select the “clear cursors” soft key on the screen menu.

d. Repeat the Cursors method for a square and triangular signal and record your measurements in the table below.

Note: In this case the oscilloscope is triggering in the internal mode.

<table>
<thead>
<tr>
<th>Type of signal</th>
<th>Amplitude (V1)</th>
<th>Period (sec) Δt</th>
<th>Frequency (Hz) 1/Δt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinusoid</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Square</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triangular</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

(9 points)
4.) Which of the two measurement methods 1 and 3 did you think was easiest for measuring voltage? Why?
……………………………………………………………………………………………………
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…………….. (2 points)

5.) Which of the two measurement methods 2 and 3 did you think was easiest for measuring time information? Why?
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…………….. (2 points)

6.) Do you think one method is more exact or accurate than the others? Why?
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9.) Change the trigger source to LINE. What happens to the signal? Describe your observations and compare with the previous case. (5 points)

10.) Select the trigger source EXTERNAL. Split the input signal and connect it to input Z by using another gray probe cable attached to the function generator. Change the triggering level using the knob in the triggering section. What happens to the horizontal position of the display? Why? (5 points)

12.) Without changing the oscilloscope set up, disconnect the probes on the cable going to the Z input on the oscilloscope. Now connect them to the “SYNC” connector on the function generator using another BNC to banana jack adapter. Now what happens to the horizontal position of the display when you vary the triggering level of the oscilloscope? “SYNC” is short for synchronization. What do you think the SYNC signal could be used for? (5 points)
II. Measuring AC Signals: (55 points)

Although oscilloscopes provide detailed pictures of AC signals, we are sometimes interested only in the magnitude of an AC signal. Especially if we already know other properties of the signal such as its waveform and frequency. In this case, a multimeter with AC reading capability is useful and typically less expensive than an oscilloscope. One complication is that multimeters usually report the root-mean-square (RMS) value of a signal. You need to understand RMS calculations in order to use multimeters appropriately for AC measurements.

Understanding RMS (Root-Mean-Square)
The RMS value of an AC voltage is obtained by first squaring the voltage, then finding the average or mean voltage over one cycle of the original signal, and then taking the square root of the average. The steps form the name of the method – square, mean, root – just in reverse. As an example, let’s find the RMS value of an AC voltage signal described by \( v = 1 \text{V} \sin(t) \). Squaring the signal gives,

\[
v^2 = 1 \sin^2(t) \quad V^2 = (1 - \cos(2t))/2 \quad V^2
\]

where a trigonometry identity has been used to express \( \sin^2(t) \) in terms of a cosine with twice the frequency. To find the average of \( v^2 \), we note that the average of any sinusoid over a cycle is zero, so the average of \( v^2 = 1V^2 \times (1/2) \). Finally, we take the square root of this to find the RMS voltage is

\[
V_{\text{RMS}} = \frac{1V}{\sqrt{2}} = 0.707V
\]

1.) For a sinusoid of 10 Vpp, amplitude 5 V, calculate the root mean square value. (3 points)
From the signal generator select three different waveforms with a peak-to-peak amplitude of 10Vpp and a frequency of 1000Hz. Enter the amplitude, Vm, in the table below. Measure the \( V_{\text{RMS}} \) value using the oscilloscope as in part 1. Then also measure the \( V_{\text{RMS}} \) value with the multimeter. To do this, connect the red lead of the multimeter to the probe where the function generator is already connected and the ground to ground. Note that it is important to connect the probe grounds and instrument grounds to only one point in the circuit, or you will short out the circuit or instruments. Select the “AC V” mode key on the multimeter since you are measuring an AC signal. Connect the multimeter leads properly for voltage measurements.

Fill in the table below with your measurements and determine the ratio of the root mean square to the amplitude: \( V_{\text{RMS}}/V_{\text{max}} \). (10 points)

<table>
<thead>
<tr>
<th>Waveform</th>
<th>Vm (V)</th>
<th>( V_{\text{RMS}}(V) ) oscilloscope</th>
<th>( V_{\text{RMS}}(V) ) multimeter</th>
<th>( V_{\text{RMS}}/V_{\text{max}} ) oscilloscope</th>
<th>( V_{\text{RMS}}/V_{\text{max}} ) multimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>sine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>triangular</td>
<td></td>
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<td></td>
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<tr>
<td>square</td>
<td></td>
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</tbody>
</table>

2.) For the sine wave, does the measured ratio of \( V_{\text{RMS}}/V_{\text{m}} \) agree with the example calculated in step #1 above? Comment on the agreement or disagreement. (2 points)

3.) Why is the ratio \( V_{\text{RMS}}/V_{\text{m}} \) as measured by the oscilloscope different for each of the waveforms? (You might think about the RMS values for square waves, for example.) (4 points)
4.) While the RMS calculation by an oscilloscope can usually be trusted, some multimeters assume that the ratio $V_{RMS}/V_m$ is always the same as for measured for sine waves. In this case, $V_{RMS}/V_m$ from the multimeter will be the same for the different waveforms even though it shouldn’t be. Did the ratios for $V_{RMS}/V_m$ from the multimeter change for different waveforms? Did they agree with the oscilloscope? If the multimeter is correctly calculating $V_{RMS}$ for different waveforms, then we say it is measuring true $V_{RMS}$. (2 points)

5.) Lastly, we want to check if the multimeter correctly measures different frequencies of signals. Measure the frequency response of the multimeter using the following steps: Set the function generator to produce a sinusoidal signal of 1.414V amplitude ($V_{FG,RMS}=1V_{RMS}$, 2.828V peak-to-peak). Vary the frequency of the input signal and record the reading of the multimeter ($V_{MM,RMS}$) in the table shown below, then calculate the ratio $V_{MM,RMS}/V_{FG,RMS}$ which is generally expressed in log scale, or in decibels. As you proceed you should also monitor the signal with the oscilloscope to make sure that the function generator output is not changing with frequency. Record the RMS measurements using the oscilloscope in the table under the column $V_{OSC,RMS}$.

\[
\left[ \frac{V_{out}}{V_{in}} \right]_{dB} = 20 \log_{10} \left( \frac{V_{out}}{V_{in}} \right)
\]

\[
\uparrow \quad \uparrow
\]

in decibels \hspace{1cm} unitless

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>$V_{OSC,RMS}$</th>
<th>$V_{MM,RMS}$</th>
<th>$V_{MM,RMS}/V_{FG,RMS}$</th>
<th>$V_{MM,RMS}/V_{FG,RMS}$ [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td></td>
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<tr>
<td>100</td>
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<td>1000</td>
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<td>2000</td>
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<td>6000</td>
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<tr>
<td>8000</td>
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</tbody>
</table>
4.) Using MATLAB, plot $V_{MM, RMS}/V_{FG, RMS}$ versus frequency both in linear and in dB scales for the y-axis. Use a log scale for the frequency x-axis. Attach your plots to the report. (10 points)

5.) Comment on the plots including any differences in the two types of plots. (5 points)

6.) Suggest a reason why the ratio $V_{MM, RMS}/V_{FG, RMS}$ would change with frequency. You may find it helpful to refer to the specifications page on the manual for the multimeter. You may also find it interesting to do the same thing for the oscilloscope. (5 points)
Objective: To become familiar with the current and voltage relationship of capacitors and inductors and to learn how to use the oscilloscope to measure phase differences and differential voltages.

* Equipment list:

1. MB Board and components
2. Oscilloscope
3. Function Generator
4. Resistor 100Ω, 1kΩ
5. Capacitor 0.01µF
6. Inductor 1mH

* Introduction:

In the last experiment you became familiar with instrumentation used to generate and measure AC signals and examined the frequency response of a multimeter. In this experiment you will examine the current–voltage relationship for capacitors and inductors using sinusoidal excitation. You will examine not only the magnitude of the voltages in the circuits but also the relationships between the phases of different circuit voltages and current.

Part I. AC Circuit Components – Capacitors and Inductors

A. Capacitor Impedance

In this section you will examine the relationship between the current and voltage for a capacitor using sinusoidal waveforms. Capacitors store electrostatic energy, and the current through them is determined by the rate of change of the voltage. If the voltage across the capacitor is sinusoidal then so is its current, but they will have different phases. The relationship between the peak amplitude of the current and voltage sinusoids is determined by the magnitude of the capacitor’s AC impedance which is a function of frequency. Both the amplitude and phase relationship between a capacitor’s current and voltage are expressed in the capacitor’s complex impedance which is defined as:

\[ \hat{Z}(\omega) = \frac{\hat{V}(\omega)}{\hat{I}(\omega)} \]
where $\omega = 2\pi f$ is the angular frequency. The voltage across the capacitor can be viewed directly with an oscilloscope. However, to measure the current through the capacitor, we must use either special current probes or another technique since oscilloscopes typically only measure voltage. For this experiment, we will put a known resistor in series with the capacitor as shown below in Figure 1. Since the series resistor and capacitor must have the same current, and the resistor current is directly proportional to the resistor voltage, we can determine the capacitor current by observing the resistor voltage. A series resistor used for measuring current is sometimes referred to as a “current viewing resistor”. We’ve chosen a resistor that is a power of 10 to simplify converting voltage to current.

One additional complication is that we cannot connect a single oscilloscope probe across the resistor in order to measure its voltage because as seen in Figure 1 neither end of the resistor is connected to ground (the negative terminal of the voltage source). Connecting the ground lead of the oscilloscope probe to either end of the resistor would short that point to ground thus shorting out either the function generator or the capacitor. Instead, we will measure the voltage across the capacitor, $V_C$, and the voltage across the source, $V_{in}$, since both of these elements are connected to ground. Then we will use the ability of the oscilloscope to display a difference (i.e. subtraction) signal, $V_{in} - V_C$, to show the voltage across the resistor.

1. Construct the circuit shown in the Figure 1 using $R = 1\text{k}\Omega$ and $C = 0.01\mu\text{F}$. Drive the circuit with a sinusoidal signal of amplitude 10V peak-to-peak from the function generator. Connect channel 1 of the oscilloscope across the source voltage, $V_{in}$, and channel 2 of the oscilloscope across the capacitor, making sure to connect both oscilloscope probe grounds to the common node between the function generator and capacitor. (This should also be the ground terminal of the function generator.) Make sure that both channels are set to the same vertical Volts/Div setting. Throughout this experiment, you may adjust the vertical Volts/Div settings, but both channels must have the same setting or else the channel subtraction will give you erroneous readings. You should also adjust the vertical position of both channels so that the zero level indicated by a small ground symbol at the right edge of the screen is exactly in the middle. Do this for both channels. Turn on the display for channel 1 and channel 2. Now, press the +/- key between the two channels and select “1-2”.

![Figure 1](image)
This will show the difference in the voltage between the two channels, i.e. the voltage across the resistor. There will now be three sinusoidal traces on the screen.

One of the difficulties in this experiment is keeping track of which trace corresponds to which voltage. Be sure that channel 1 is connected across the function generator. You should also make sure that channel 1 is selected as the source for triggering. To reduce confusion over the traces, it is best to disable the display of channel 1 unless you are using it to check the amplitude of the signal from the function generator. To disable the display of channel 1, press the “1” button next to the channel 1 controls and use the soft keys to toggle the display of channel 1 to “off”. Even though channel 1 is not displayed, the difference between channel 2 and channel 1 (i.e. 2-1) will still be correctly displayed as long as both channels are set to the same vertical Volts/Div setting. You may still become confused even with only two traces displayed. To determine which trace is the capacitor voltage, you may squeeze the orange button on the channel 2 oscilloscope probe connected to the capacitor. The oscilloscope probe will be disconnected (open circuited) while the orange button is depressed. Thus momentarily pressing the channel 2 probe button will make the capacitor voltage trace drop to zero temporarily, allowing you to identify it.

IMPORTANT LAST WARNING: IF YOU HAVE NOT ALREADY CAREFULLY READ EVERY WORD ABOVE AND REREAD THE SECTION ON PROPER OSCILLOSCOPE USE YOU ARE LIKELY TO MAKE MISTAKES THAT WILL WASTE YOUR TIME.

2. Vary the frequency of the signal according to the table shown below, then measure the peak voltage across the capacitor, \( V_C \), and the resistor, \( V_R \), using a method of your choice (e.g. cursors, built-in measurements, etc.). Record the values of the peak voltages in the left-hand columns of the table.

| Frequency (kHz) | \( V_{in} \) (V) | \( V_C \) (V) | \( V_R \) (V) | \( I = \frac{V_R}{1k\Omega} \) | \( |Z| = \frac{|V_C|}{|I|} \) (\( \Omega \)) | \( \Delta t_{V-I} \) (s) | Phase of \( V_C \) – phase of \( I \) |
|----------------|-----------------|--------------|--------------|------------------|------------------|----------------|------------------|
| 1              |                 |              |              |                  |                  |                |                  |
| 10             |                 |              |              |                  |                  |                |                  |
| 100            |                 |              |              |                  |                  |                |                  |
| 1000           |                 |              |              |                  |                  |                |                  |

(30 points)

3. Now calculate the current through the capacitor (which is the same as the current through the resistor) at each frequency and enter it in the appropriate column above. Finally, calculate the magnitude of the capacitor’s impedance, \( |Z| \), by dividing the peak amplitude of the capacitor voltage by the peak amplitude of the capacitor current, and enter this value in the appropriate column.
4. Graph $|Z|$ vs. frequency on both a linear-linear plot and log-log plot and attach the plot to your report. (10 points)

5. What function do you think fits this data? Write an equation for $|Z|$ as a function of frequency. Hopefully your equation will include the value of the capacitor, the frequency, and some constants. (5 points)

6. $Z$ should be a complex number, i.e. a phasor. So far, you have determined the magnitude of $Z$, but still need to determine the phase of $Z$. To do this, you will need to look at the phase difference between $V_C$ and $I$ in the circuit above. Set the source frequency to 100 kHz. Measure the length of one period of $V_C$ by positioning the time cursors onto the zero crossings of $V_C$ one cycle apart. What is the period of the signal? Does this agree with the value you would expect from the frequency setting? (1 points)

7. Now you need to measure the phase difference between the capacitor voltage, $V_C$, and the capacitor current, $I$. Place cursor $t_1$ on the zero crossing of $V_C$ where $V_C$ is increasing with time. Place cursor $t_2$ on the zero crossing of $I$ where $I$ is increasing with time. Remember that $v_R$ is proportional to $I$, so use the $v_R$ waveform to determine the zero crossing of $I$. Choose the zero crossing that is closest to $t_1$ but make sure that it is a zero crossing where $I$ is increasing. Record the time difference in the $\Delta t_{V-I}$ the time column of the table above. Be sure to include the appropriate sign; if $t_1$ occurs before $t_2$, then the voltage leads the current and $\Delta t_{V-I}$ is positive. If $t_1$ occurs after $t_2$, then the voltage lags the current and $\Delta t_{V-I}$ is negative. Finally, divide $\Delta t_{V-I}$ by the period and multiply by $2\pi$ radians to calculate the phase difference. Enter the phase difference in the final column. Draw a sketch below of the $V_C$ and $I$ waveforms showing the phase difference.
8. Repeat steps 6 and 7 for the other frequencies in the table. Be sure and divide by the correct period to calculate the phase difference. You may be tempted to change one of the channel’s vertical scales to increase the signal for a more accurate measurement of the zero crossings. Remember that both channels must be on the same vertical scales (Volts/Div) in order for channel subtraction to work correctly. (A “feature” of our oscilloscopes.) Of course, you may change the horizontal time base scale (Secs/Div) to get more accurate readings as horizontal scale setting changes all channels together.

9. What happens to the phase difference as a function of frequency? Does this agree with the expression you’ve learned in class for the complex impedance of a capacitor? Note that the phases you measured at the maximum and minimum frequencies may not be accurate because of the small amplitude of the voltage across one of the components causing measurement errors (4 points) .

\[ \text{B. Inductor Impedance} \]

You will now repeat the same type of measurement you did above for an inductor. Inductors store magnetic energy, and the voltage across them is determined by the rate of change of the current. Again, both voltage and current will be sinusoidal in this experiment, but they will have different phases. The ratio of the voltage magnitude to current magnitude as well as the phase relationship will again determine the inductor’s complex impedance. Please follow the same precautions mentioned above when connecting oscilloscope probes to the circuit shown in Figure 3. Connect channel 1 across Vin and channel 2 across the inductor.

1. Construct the circuit shown in the Figure 3 using \( R=100\Omega \) and \( L=1\text{mH} \). Drive the circuit with a signal of amplitude 10V peak-to-peak from the function generator. Connect channel 1 of the oscilloscope across Vin and channel 2 of the oscilloscope across the inductor, making sure to connect both oscilloscope probe grounds to the common node between these two elements. Turn on the difference between the two channels to display the voltage across the resistor.

2. Vary the frequency of the signal according to the table shown below, then measure the peak voltage across the inductor, \( V_L \), and the resistor, \( V_R \). Record the values of the peak voltages in the left-hand columns of the table.
### Frequency (kHz) | $V_{in}$ (V) | $V_{L}$ (V) | $V_{R}$ (V) | $I = \frac{V_{R}}{100\Omega}$ | $|Z| = \frac{|V_{L}|}{|I|}$ (Ω) | $\Delta \tau_{V-I}$ (s) | Phase of $VL$– phase of $I$

| 0.1 |
| 1 |
| 10 |
| 100 |
| 1000 |

(30 points)

3. Calculate the current through the inductor (and thus the resistor) as well as the magnitude of the inductor’s impedance $|Z|$ at each frequency and enter these data in the appropriate columns above. Graph $|Z|$ vs. frequency on both a linear-linear plot and log-log plot and attach the plots to your report. (10 points)

4. What function do you think fits this data? Write an equation for $|Z|$ as a function of frequency. Hopefully your equation will include the value of the inductor and some constants. (5 points)

5. Perform phase difference measurements for each frequency as described above in the section on capacitors. Remember, if the positive-going zero-crossing of $v_{L}$ occurs before the positive-going zero-crossing of $i$, then the voltage leads the current and $\Delta \tau_{V-I}$ is positive; otherwise, the opposite is true. Draw a sketch below of the $v_{L}$ and $i$ waveforms showing the phase difference at $f=10$kHz.
6. What happens to the phase difference as a function of frequency? Does this agree with the expression you’ve learned in class for the complex impedance of an inductor? Again, remember that the phases calculated at the minimum and maximum frequencies may not be accurate due to measurement errors. (4 points)
**Experiment #9**

**Building practical circuits**

| Objective: Use the concepts acquired during the semester along with some “new” components to build practical circuits. |

* Equipment list:

1. A MR magnetic board
2. A set of components

In this laboratory practice you will use concepts learnt during the semester to build few examples of circuits with practical applications. In this laboratory you will used the magnetic board and a set of components included in the laboratory set. Among these elements are some new components that you will use by the first time.

1. **Simple Photoresistor (Light Detection) Circuit**

A photoresistor or light dependent resistor (LDR) is a resistor whose resistance depends on the light incident on the element, specifically, the resistance of a photoresistor decreases with the intensity of light.

A Light Emitting Diode (LED) is one of the most common components utilized in light displays, signaling, illumination, etc. The LED is like the diode we analyzed in experiment 4, but it emits light when sufficient current flows from the anode to the cathode typically on the order of a few mA.

In the set of elements at your disposal you will find an LED and a photoresistor. With these elements connect the circuit described in the figure using your magnetic prototype board.
The circuit layout in the magnetic board should look like the figure below

![Circuit Diagram]

Connect the circuit. Describe what happens when you change the amount of light incident on the photoresistor. Explain your findings using your knowledge about what is happening.

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2- Light Sensor Circuit with “Transistor Switch”

With the experience acquired testing the former circuit, we will set up a light sensor using a bipolar transistor available in the laboratory set. A bipolar transistor is a device that can be used as a switch or as an amplifier. It has three contacts labeled “base” (B), “collector” (C), and “emitter” (E). The transistor allows for the control of large currents flowing between the collector and emitter by controlling a small signal applied between the base and the emitter. The typical regimes of operation of a transistor are:

• Active: If the base–emitter is forward biased and the base–collector reverse biased the transistor is in the “Active” regime. In this regime the current flowing from the collector to the emitter is proportional to the current flowing from the base to the emitter.

• Saturation: Both B-E and B-C are forward-biased. In this situation the transistor operates as a switch -- “ON”.

• Cutoff: With the biasing conditions opposite of saturation (both reverse biased) the transistor behaves as a switch -- "off".
Aside Comment: There are two types of bipolar resistors, NPN and PNP. In this lab we will use a NPN bipolar transistor. The NPN transistor shown in the figure below shows a diode-like symbol on the emitter side pointing outward. For a PNP transistor the diode symbol points inward. So how do you remember which is which? Here’s our pneumonic. NPN – Not Pointed iN.

Connect the circuit described in the figure below

The circuit layout in the magnetic board should look like the figure below
Connect the circuit. Describe what happens when you change the amount of light incident on the photoresistor. Explain, using your knowledge, what is happening.