Contents

LAB 1: OHM'S LAW ... 4
1. EQUIPMENT ... 4
2. INTRODUCTION ... 4
3. THEORY ... 4
4. EXPERIMENT ... 6
Ohm's Law ... 6
LAB 2: RESISTANCES IN CIRCUITS ... 9
1. EQUIPMENT ... 9
2. INTRODUCTION ... 9
3. THEORY ... 9
3.1 Resistor in series ... 9
3.2 Resistor in parallel ... 9
4. EXPERIMENT ... 11
4.1 Same resistors ... 11
4.2 Different resistors ... 13
LAB 3: LRC CIRCUIT ... 15
1. EQUIPMENT ... 15
2. INTRODUCTION ... 15
3. THEORY ... 15
3.1 LC Oscillations ... 15
3.2 Resistive Circuit ... 15
3.3 Capacitive Circuit ... 16
3.4 Inductive Circuit ... 16
3.5 LRC Circuit ... 16
4. EXPERIMENT ... 18
4.1 LC Oscillations ... 18
4.1.1 Set up ... 18
4.1.2 Procedure ... 18
4.2 Resistive Circuit ... 19
4.2.1 Set up ... 19
4.2.2 Procedure ... 19
4.3 Capacitive Circuit ... 19
4.3.1 Set up ... 19
4.3.2 Procedure ... 20
4.4 Inductive Circuit ... 20
4.4.1 Set up ... 20
4.4.2 Procedure ... 21
4.5 LRC Circuit ... 21
4.5.1 Set up ... 21

4.5.2 Procedure 21
5. QUESTIONS 22
LAB 4: KIRCHHOFF'S LAW 23
1. EQUIPMENT 23
2. INTRODUCTION 23
3. THEORY 23
3.1 Kirchhoff's Current Law: 23
3.2 Kirchhoff's Voltage Law: 24
4. EXPERIMENT 26
4.1 Setup - Procedure 26
4.2 Analyzing the Data 27
4.3 Discussion 27
4.4 Extension 28
LAB 5: RC CIRCUIT 29
1. EQUIPMENT 29
2. INTRODUCTION 29
3. THEORY 29
3.1 Exponential Charge and Discharge 29
3.2 The Time Constant τ and the Half Life $\boldsymbol{t12}$ 30
3.3 Charging for One Time Constant 30
3.4 Discharging for One Time Constant 30
3.5 The Time to Fully Charge the Capacitor 30
3.6 The Positive Square Voltage Wave 31
4. EXPERIMENT 32
4.1 Equipment Setup 32
4.2 Procedure 32
4.2.1 Charging the Capacitor 32
4.2.2 Discharging the Capacitor 33
LAB 6: LR CIRCUIT 36
1. EQUIPMENT 36
2. INTRODUCTION 36
3. THEORY 36
4. EXPERIMENT 38
4.1 Computer Setup 38
4.2 Sensor Calibration and Equipment Setup 38
4.3 Data Recording 39
4.4 Analyzing the Data 39
4.5 Questions 40
4.6 Extension 40
LAB 7: MAGNETIC FIELDS OF COILS 41
1. EQUIPMENT 41

2. INTRODUCTION 41
3. THEORY 42
3.1 Single Coil 42
3.2 Two Coils 43
3.3 Solenoid 44
4. EXPERIMENT 45
4.1 Set Up 45
4.2 Single coil procedure 46
4.3 Two coils procedure 46
4.4 Solenoid procedure 47
LAB 8: ELECTRON CHARGE TO MASS RATIO EXPERIMENT 49
1. EQUIPMENT 49
2. INTRODUCTION 49
3. THEORY 49
4. EXPERIMENT 50
4.1 Adjust Operating Voltages and Current 50
4.2 Record Data: Standalone 51
4.3 Analysis of e/m Measurements 51

LAB 1: OHM'S LAW

1. EQUIPMENT

1	AC/DC Electronics Lab Board	EM-8656
1	Wire Leads, Resistors	
1	D-cell Battery	
2	Multi-meter	

2. INTRODUCTION

The purpose of this lab is

2.1. To become familiar with the Circuits Experiment Board, to learn how to construct a complete electrical circuit, and to learn how to represent electrical circuits with circuit diagrams.

2.2. To determine how light bulbs behave in different circuit arrangements. Different ways of connecting two batteries will also be investigated.

2.3. To investigate the three variables involved in a mathematical relationship known as Ohm's Law.

3. THEORY

Many of the key elements of electrical circuits have been reduced to symbol form. Each symbol represents an element of the device's operation, and may have some historical significance. In this lab and the ones which follow, we will use symbols frequently, and it is necessary you learn several of those symbols.

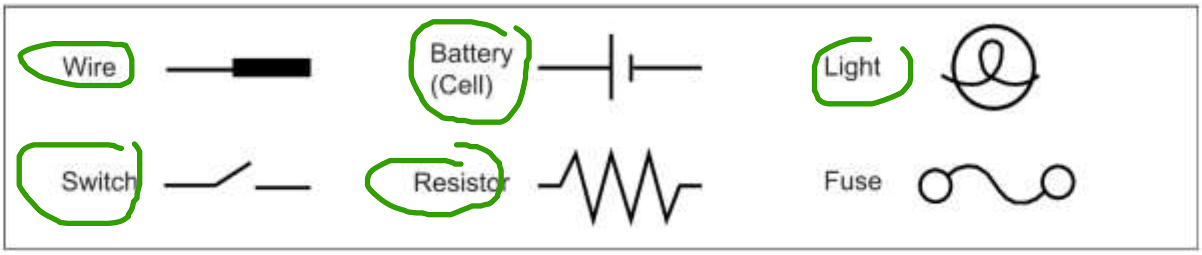


Figure 1.1

OHM'S LAW

Ohm discovered that when the voltage (potential difference) across a resistor changes, the current through the resistor changes. He expressed this as

$$\boxed{I = \frac{V}{R}} \qquad R = \frac{V}{I} \tag{1.1}$$

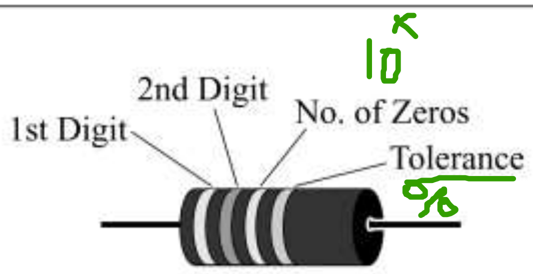
where I is current, V is voltage (potential difference), and R is resistance. Current is directly proportional to voltage and inversely proportional to resistance. In other words, as the voltage increases, so does the current. The proportionality constant is the value of the resistance. Since the current is inversely proportional to the resistance, as the resistance increases, the current decreases.

A resistor is 'Ohmic' if as voltage across the resistor is increased, a graph of voltage versus current shows a straight line (indicating a constant resistance). The slope of the line is the value of the resistance.

APPENDIX

Resistor color codes

Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9



Fourth Band	
None	±20%
Silver	±10%
Gold	±5%
Red	±2%

Figure 1.2

----- End of Theory-----

4. EXPERIMENT

Ohm's Law

1. Choose one of the resistors that you have been given. Using the chart on the next page, decode the resistance value and record that value in the first column of Table 1.1.

2. **MEASURING CURRENT:** Construct the circuit shown in Figure 1.3 by pressing the leads of the resistor into two of the springs on the Circuits Experiment Board.

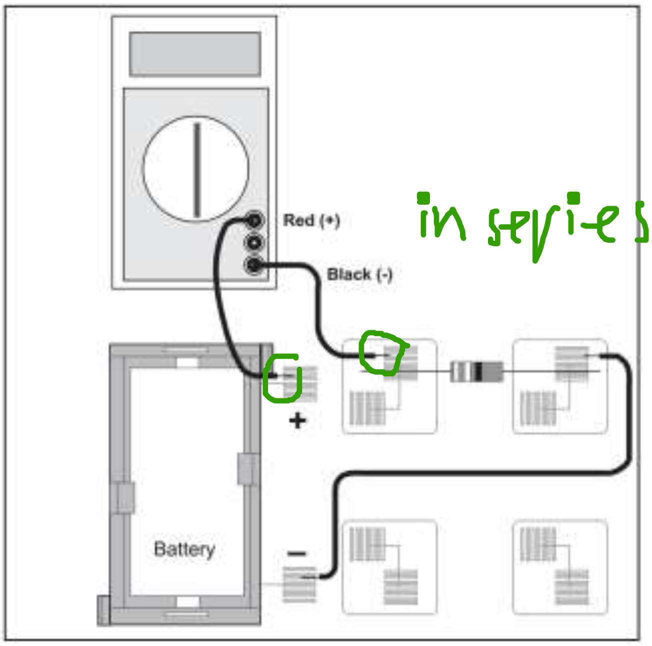


Figure 1.3

3. Set the Multi-meter to the AMPERE range, noting any special connections needed for measuring current. Connect the circuit and read the current that is flowing through the resistor. Record this value in the second column of Table 1.1.

4. Remove the resistor and choose another. Record its resistance value in Table 1.1 then measure and record the current as in steps 2 and 3. Continue this process until you have completed all of the resistors you have been given. As you have more than one resistor with the same value, keep them in order as you will use them again in the next steps.

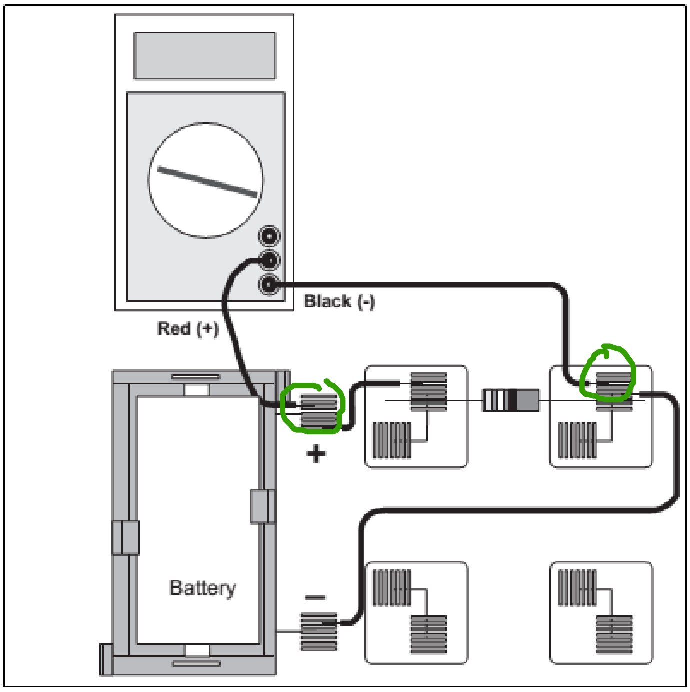


Figure 1.4

5. **MEASURING VOLTAGE**: Disconnect the Multi-meter and connect a wire from the positive lead (spring) of the battery directly to the first resistor you used as shown in Figure 1.4. Change the Multi-meter to the 2 VDC scale and connect the leads as shown also in Figure 1.4. Measure the voltage across the resistor and record it in Table 1.1.

6. Remove the resistor and choose the next one you used. Record its voltage in Table 1.1 as in step 5. Continue this process until you have completed all of the resistors.

Table 1.1

No	Resistance, ohm		Voltage, volt	Current, amp	Voltage/ Resistance	%Error
	Average value of R	The tolerance limit of R				
1	dien tro	sai so	U	I	I	
2						
3						
4						
5						

7. Construct a graph of Current (vertical axis) vs. Resistance.

8. For each of your sets of data, calculate the ratio of Voltage/Resistance. Compare the values you calculate with the measured values of the current.
9. From your graph, what is the mathematical relationship between Current and Resistance?
10. Ohm’s Law states that current is given by the ratio of voltage/resistance. Does your data concur with this?
11. What were possible sources of experimental error in this lab? Would you expect each to make your results larger or to make them smaller?

LAB 2: RESISTANCES IN CIRCUITS

1. EQUIPMENT

1	AC/DC Electronics Lab Board	EM-8656
1	Wire Leads, Resistors	
1	D-cell Battery	
2	Multi-meter	

2. INTRODUCTION

The purpose of this lab is to begin experimenting with the variables that contribute to the operation of an electrical circuit: resistances, currents, voltages.

3. THEORY

3.1 Resistor in series

When resistors are connected in series, the **current** through each resistor is the same. In other words, the current is the same at all points in a series circuit.

When resistors are connected in series, the total potential difference across all the resistors is equal to the sum of the potential differences across each resistor. In other words, the potential differences around the circuit add up to the potential difference of the supply.

The total resistance of a number of resistors in series is equal to the sum of all the individual resistances.

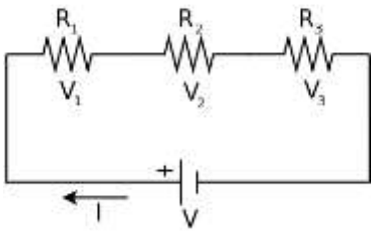


Figure 2.1

In the circuit above, the following applies

$$\boxed{I_1 = I_2 = I_3;\ V_T = V_1 + V_2 + V_3}$$

And so, therefore, $\boxed{R_T = R_1 + R_2 + R_3}$

3.2 Resistor in parallel

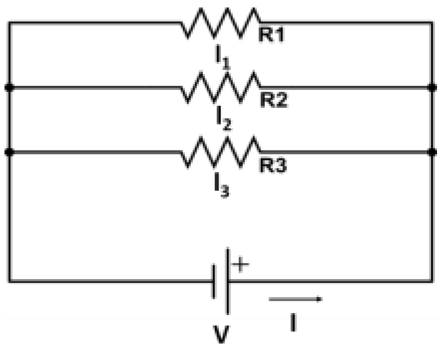


Figure 2.2

When resistors are connected in parallel, the supply **current** is equal to the sum of the currents through each resistor. In other words the currents in the branches of a parallel circuit add up to the supply current.

When resistors are connected in parallel, they have the same **potential difference** across them. In other words, any components in parallel have the same potential difference across them.

For the circuit above, the formula for finding the **total resistance** of resistors in parallel is $1/R_T = 1/R_1 + 1/R_2 + 1/R_3$

$$\boxed{I_T = I_1 + I_2 + I_3;\ V_1 = V_2 = V_3}$$

And so $\boxed{1/R_T = 1/R_1 + 1/R_2 + 1/R_3}$

----- End of Theory-----

4. EXPERIMENT

4.1 Same resistors

SERIES

1. Choose three resistors of the same value. Enter those sets of colors in Table 2.1 below. We will refer to one as #1, another as #2 and the third as #3.
2. Determine the coded value of your resistors. Enter the value in the column labeled "Coded Resistance" in Table 2.1. Enter the Tolerance value as indicated by the color of the fourth band under "Tolerance".
3. Use the Multi-meter to measure the resistance of each of your three resistors. Enter these values in Table 2.1.
4. Determine the percentage experimental error of each resistance value and enter it in the appropriate column.

$$\text{Experiment error} = \frac{|\text{Measured - Code}|}{\text{Code}} \times 100\%$$

Table 2.1

	Colors 1st	2nd	3rd	4th	Coded Resistance	Measured Resistance	% Error	Tolerance
#1								
#2								
#3								

5. Now connect the three resistors into the SERIES CIRCUIT, figure 2.3, using the spring clips on the Circuits Experiment Board to hold the leads of the resistors together without bending them. Measure the resistances of the combinations as indicated on the diagram by connecting the leads of the Multi-meter between the points at the ends of the arrows.

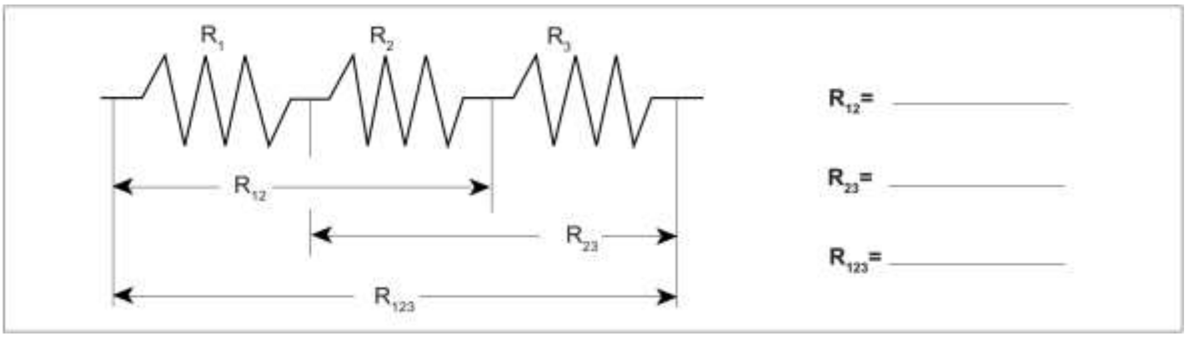


Figure 2.3

PARALLEL

6. Construct a PARALLEL CIRCUIT as in figure 2.4, first using combinations of two of the resistors, and then using all three. Measure and record your values for these circuits.

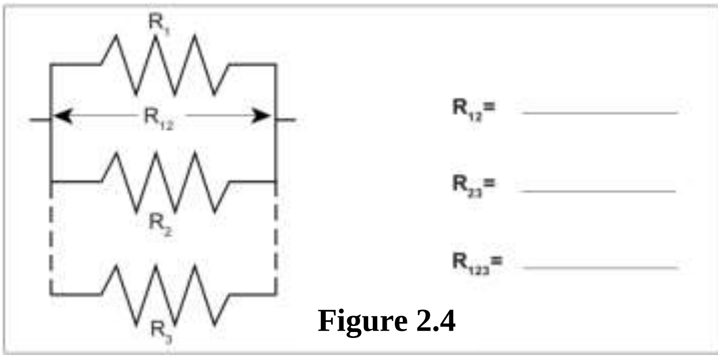


Figure 2.4

➤ **NOTE:** Include also $\mathbf{R_{13}}$ by replacing $\mathbf{R_2}$ with $\mathbf{R_3}$.

COMBINATION

7. Connect the COMBINATION CIRCUIT below (figure 2.5) and measure the various combinations of resistance. Do these follow the rules as you discovered them before?

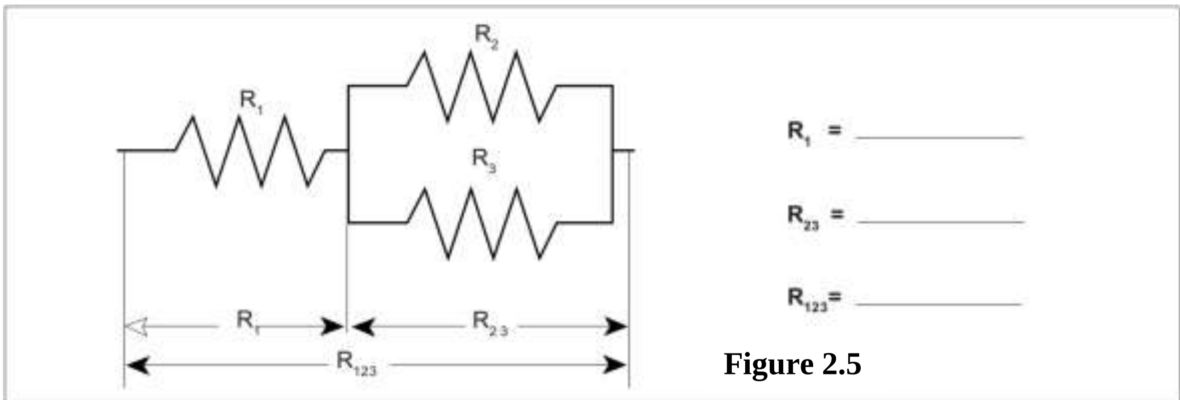


Figure 2.5

4.2 Different resistors

1. Choose three resistors having different values. Repeat steps 1 through 7 as above, recording your data in the spaces on the next page. Note we have called these resistors A, B and C.

Table 2.2

	Colors 1st	2nd	3rd	4th	Coded Resistance	Measured Resistance	% Error	Tolerance
A								
B								
C								

SERIES

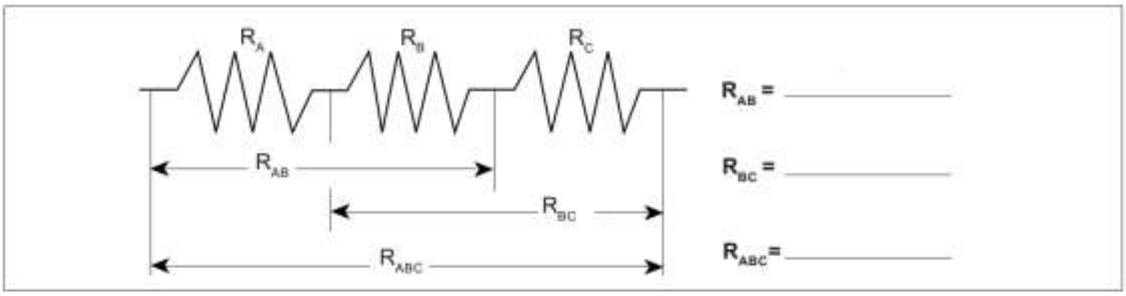


Figure 2.6

PARALLEL

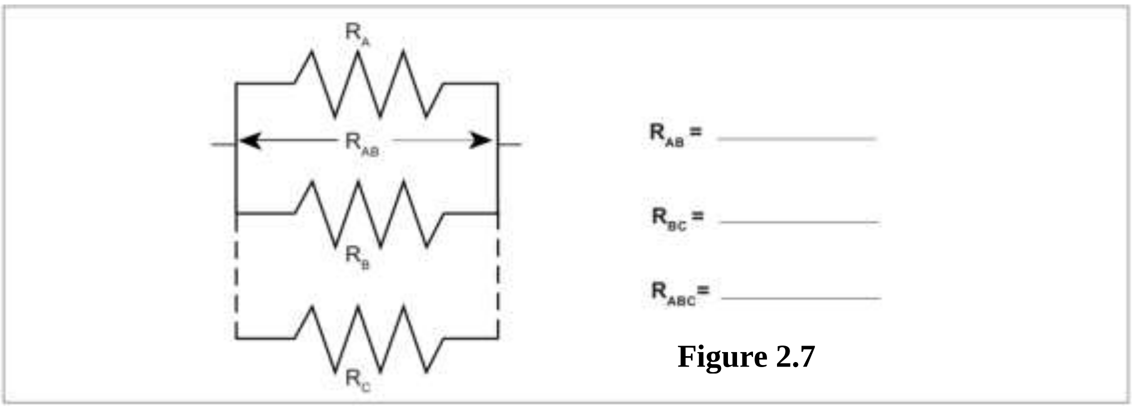
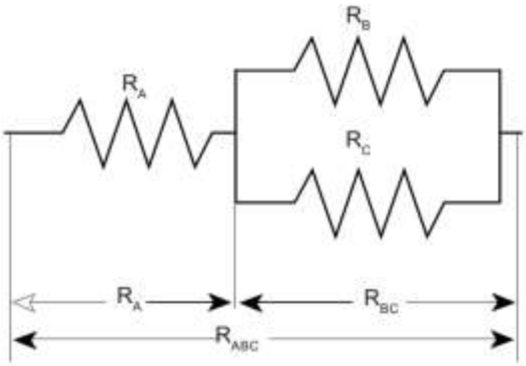


Figure 2.7

➤ **NOTE:** Include also $\mathbf{R_{AC}}$ by replacing $\mathbf{R_B}$ with $\mathbf{R_C}$.

COMBINATION



R_A = ____________

R_{BC} = ____________

R_{ABC}= ____________

Figure 2.8

LAB 3: LRC CIRCUIT

1. EQUIPMENT

INCLUDED		
1	AC/DC Electronics Laboratory	EM- 8656
3	Voltage Sensor	CI-6503
NOT INCLUDED, BUT REQUIRED		
1	ScienceWorkshop 750 Interface	CI-7650
1	DataStudio Software	

2. INTRODUCTION

A square wave voltage is applied to an LC circuit and the period of oscillation of the voltage across the capacitor is measured and compared to the theoretical value. Then three AC circuits are examined: A sinusoidal voltage is applied individually to a resistor, a capacitor, and an inductor. The amplitude of the current and the phase difference between the applied voltage and the current are measured in each of the three circuits to see the effect each component has on the current. Finally, a sinusoidal voltage is applied to an inductor, resistor, and capacitor in series.

The amplitude of the current and the phase difference between the applied voltage and the current are measured and compared to theory.

3. THEORY

3.1 LC Oscillations

A low frequency square wave voltage is applied to an inductor and capacitor series circuit. This charges the capacitor. Then the capacitor discharges through the inductor and the voltage across the capacitor oscillates at the resonant frequency of the LC circuit,

$$\boxed{\omega = \frac{1}{\sqrt{LC}}} \qquad \omega = \frac{1}{\sqrt{LC}} = 2\pi f \tag{3.1}$$

3.2 Resistive Circuit

A resistive circuit is one in which the dominant component is resistance. In this experiment, a voltage $V = V_{max}\sin(\omega t)$ is applied to a resistor alone. The current, I, through the resistor is in phase with the applied voltage:

$$I = I_{max}\sin(\omega t) \tag{3.2}$$

where the maximum current, I_{max}, is equal to V_{max}/R.

3.3 Capacitive Circuit

A capacitive circuit is one in which the dominant component is capacitance. In this part of the experiment, a voltage $V = V_{max}\sin(\omega t)$ is applied to a capacitor alone. Since the voltage across the capacitor is

$$V = \frac{Q}{C} = V_{max}\sin(\omega t) \tag{3.3}$$

where Q is the charge on the capacitor and C is the capacitance. Solving for Q and $= \frac{dQ}{dt}$, the phase difference between the current through the capacitor and the applied voltage is π/2. The current through the capacitor is given by

$$I = I_{\max}\cos\omega t = I_{\max}\sin(\omega t + \frac{\pi}{2}) \tag{3.4}$$

where $I = \frac{V_{max}}{\chi_C}$ and the capacitive reactance is

$$\chi_C = \frac{1}{\omega C} \tag{3.5}$$

3.4 Inductive Circuit

An inductive circuit is one in which the dominant component is inductance. In this part of the experiment, a voltage $V = V_{max}\sin(\omega t)$ is applied to an inductor alone. Note that the resistance of the inductor is ignored in the theory. The voltage across the inductor is

$$V = L\frac{dI}{dt} = V_{max}\sin(\omega t) \tag{3.6}$$

where I is the current through the inductor and L is the inductance. Solving for I, we have

$$I = -I_{\max}\cos\omega t = I_{\max}\sin(\omega t - \frac{\pi}{2}) \tag{3.7}$$

The phase difference between the current through the capacitor and the applied voltage is -π/2.

3.5 LRC Circuit

A voltage $V = V_{max}\sin(\omega t)$ is applied to an inductor, capacitor, and resistor in series. The resulting current is given by

$$I = I_{max}\sin(\omega t + \phi) \tag{3.8}$$

where $I_{max} = \frac{V_{max}}{Z}$ and Z is the impedance,

$$Z = \sqrt{R^2 + (\chi_C - \chi_L)^2} \tag{3.9}$$

The phase constant (ϕ) is the phase difference between the current and applied voltage. Note that with the sign convention used here, ϕ is positive when the current leads the emf (V).

$$\tan\phi = \frac{\chi_C - \chi_L}{R} \tag{3.10}$$

-------------- End of Theory-------------------

4. EXPERIMENT

4.1 LC Oscillations

4.1.1 Set up

1. Connect the output voltage to the input banana jacks on the AC/DC circuit board using banana plugs. Connect the inductor and 10μF capacitor in series with the applied voltage as shown in Figure 3.1. IMPORTANT: Insert the iron core into the inductor.

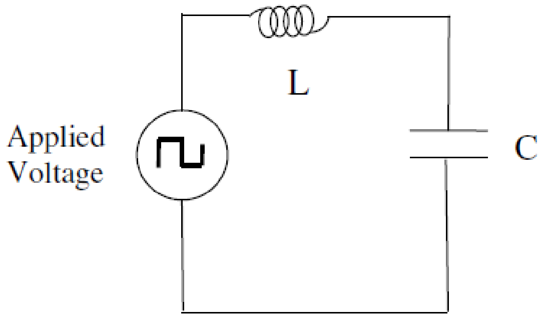


Figure 3.1: *LC* circuit

2. Open the DataStudio file called "LC Circuit". Set the 750 signal generator on a 3-Volt square wave having a frequency of 30 Hz. The 750 interface automatically measures the applied voltage and the resulting current. No Voltage Sensors are needed for this part of the experiment.

4.1.2 Procedure

1. Click on START. Adjust the time axis on the oscilloscope so that about one cycle of the square wave is visible. Click STOP.
2. For more exact measurements, click on the Applied Voltage box on the right of the oscilloscope and click on the data export button at the top of the oscilloscope. This will make a data file for the voltage.
3. Click on the Current box on the right of the oscilloscope and click on the data export button at the top of the oscilloscope. This will make a data file for the current.
4. Click on the data graph and use the Smart Cursor to measure the period of the LC oscillation. Use $f = \frac{1}{T}$ to find the frequency.
5. Using the theoretical resonant frequency in Equation (3.1) and assuming the capacitance is its stated value, calculate the inductance of the inductor with the core. Note that the equation has the angular frequency but the linear frequency was found from the graph.

6. Convert the angular frequency to linear frequency using $f = \frac{\omega}{2\pi}$.

4.2 Resistive Circuit

4.2.1 Set up

1. Change the circuit to a 10 Ω resistor in series with the applied voltage as shown in Figure 3.2.

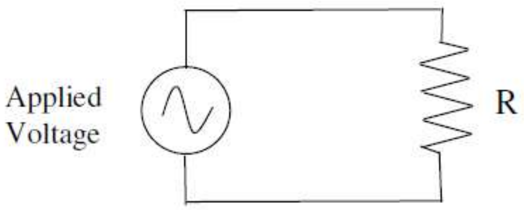


Figure 3.2: Resistive Circuit

2. Open the DataStudio file called "R Circuit". Set the 750 signal generator on a 3-Volt sine wave having a frequency of 100 Hz. The 750 interface automatically measures the applied voltage and the resulting current. No Voltage Sensors are needed for this part of the experiment.

4.2.2 Procedure

1. Click on START. Adjust the time axis on the oscilloscope so that one or two cycles of the wave are visible. Click STOP.
2. Use the Smart Cursor to examine the phase difference between the applied voltage and the current. The phase difference is the angle between the peaks of the two sine waves. It is calculated using

$T = \frac{1}{f}$

$$\phi = \frac{\Delta T}{T} \times 360° \text{ or } \phi = \frac{\Delta T}{T} \times 2\pi \text{ radians} \tag{3.11}$$

ΔT is the time between the peak of one wave and the peak of the other wave. T is the period of the waves which is the inverse of the applied frequency.

3. What is the phase difference between the resistor voltage and the current?
4. Increase the frequency of the applied voltage to 1000 Hz. Does the phase difference change? Does the magnitude of the current change?

4.3 Capacitive Circuit

4.3.1 Set up

1. Change the circuit to a 10 μF capacitor in series with the applied voltage as shown in Figure 3.3.

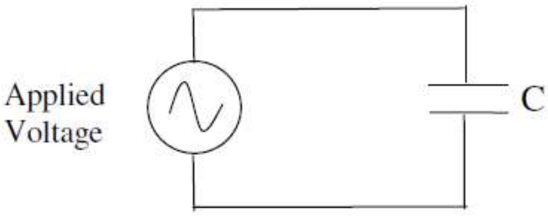


Figure 3.3: Capacitive circuit

2. Open the DataStudio file called "C Circuit". Set the 750 signal generator on a 3-Volt sine wave having a frequency of 100 Hz. The 750 interface automatically measures the applied voltage and the resulting current. No Voltage Sensors are needed for this part of the experiment.

4.3.2 Procedure

1. Click on START. Adjust the time axis on the oscilloscope so that one or two cycles of the wave are visible. Click STOP.
2. Use the Smart Cursor to examine the phase difference between the applied voltage and the current. Calculate the phase difference using Equation (3.11).
3. What is the phase difference between the capacitor voltage and the current?
4. Increase the frequency of the applied voltage to 1000 Hz. Does the phase difference change? Does the magnitude of the current change?

4.4 Inductive Circuit

4.4.1 Set up

1. Change the circuit to the inductor with the iron core in the coil in series with the applied voltage as shown in Figure 3.4.
2. Open the DataStudio file called "L Circuit". Set the 750 signal generator on a 3-Volt sine wave having a frequency of 1000 Hz. The 750 interface automatically measures the applied voltage and the resulting current. No Voltage Sensors are needed for this part of the experiment.

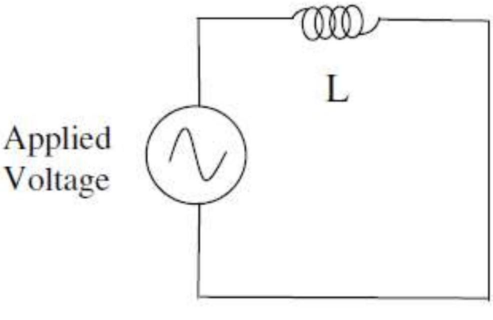


Figure 3.4: Inductive circuit

4.4.2 Procedure

1. Click on START. Adjust the time axis on the oscilloscope so that one or two cycles of the wave are visible. Click STOP.
2. Use the Smart Cursor to examine the phase difference between the applied voltage and the current. Calculate the phase difference using Equation (3.11).
3. What is the phase difference between the inductor voltage and the current?
4. Decrease the frequency of the applied voltage to 100 Hz. Does the phase difference change? Does the magnitude of the current change?

4.5 LRC Circuit

4.5.1 Set up

1. Change the circuit to the inductor with the iron core in the coil, the 10 μF capacitor, and the 10Ω resistor in series with the applied voltage as shown in Figure 3.5.

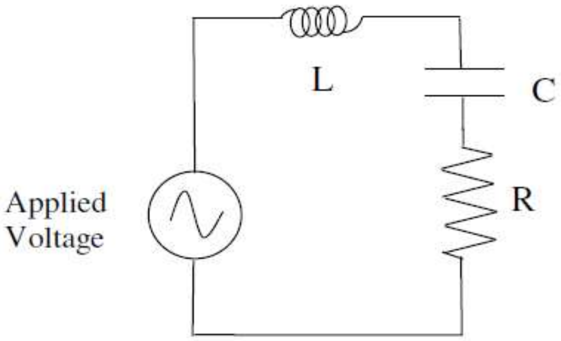


Figure 3.5: *RLC* circuit

2. Open the DataStudio file called "Resonance Curve". Set the 750 signal generator on a 3- Volt sine wave having a frequency of 20 Hz. The 750 interface automatically measures the applied voltage and the resulting current. No Voltage Sensors are needed for this part of the experiment.

4.5.2 Procedure

1. Click on START. Adjust the time axis on the oscilloscope so that one or two cycles of the wave are visible. Allow the oscilloscope to run throughout this part of the experiment.
2. Click on the Current box on the right of the oscilloscope and then use the Smart Cursor to measure the maximum current. Enter the signal generator frequency and the maximum current into the table labeled "10 Ohm".
3. Increase the signal generator frequency by 20 Hz and find the new current and record the results in the table. Continue to increase the frequency by increments you choose by

watching the resulting resonance graph. If necessary, go back and take data points at lower frequencies to fill in the resonance curve. If you go back, insert new rows into the table at the appropriate points so the connecting line on the graph will connect the points in order of frequency.

4. Continue until you reach 3000 Hz. Be sure you get enough data points around the peak.
5. Determine the frequency corresponding to the peak in the maximum current. Compare this frequency to the theoretical resonance frequency given by Equation (3.1).
6. Measure the phase difference between the current and the applied voltage at a frequency of 100 Hz, at 3000 Hz, and at the resonant frequency.
7. Replace the 10 Ω resistor with a 100 Ω resistor and repeat Steps 2 through 4. Take a smaller number of data points for this resistor, concentrating on the lower frequencies, the resonant frequency, and the higher frequencies so the general shape of the curve is distinguished.

5. QUESTIONS

1. Does the frequency of the peak maximum current correspond to the frequency of the LC oscillations? Does changing the resistance change the frequency of the peak?
2. Using Equation (3.9), calculate the theoretical peak current at resonance. Why is the actual peak current at resonance less than the theoretical?
3. Why is the peak lower for the greater resistance?
4. Explain why the phase shifts are what they are at low frequency and at high frequency and at the resonant frequency. In each case, does the current lead or lag the applied voltage? To what value does the phase shift go as the frequency goes to zero or as it goes to infinity? Which components dominate the circuit at these different frequencies?

LAB 4: KIRCHHOFF'S LAW

1. EQUIPMENT

1	AC/DC Electronics Lab Board	EM-8656
1	Wire Leads, Resistors	
1	D-cell Battery	
2	Multi-meter	

2. INTRODUCTION

The purpose of this activity is to explore Kirchhoff's two laws of electrical circuits. Use a multi-meter to measure the voltage and current across and through parts of a complex circuit.

3. THEORY

Ohm's Law describes the relationship between current, voltage, and resistance in simple circuits. Many circuits are more complex and cannot be solved with Ohm's Law. These circuits have many power sources and branches which would make the use of Ohm's Law impractical or impossible.

In 1857 the German physicist Gustav Kirchhoff developed methods to solve complex circuits. Kirchhoff produced two conclusions known today as Kirchhoff's Laws. Kirchhoff's two laws describe the unique relationship between current, voltage, and resistance in complex electrical circuits.

3.1 Kirchhoff's Current Law:

The current arriving at any junction point in a circuit is equal to the current leaving that junction. Stated another way: No matter how many paths into and out of a single point, all the current leaving that point must equal the current arriving at that point. This law is sometimes called the *junction rule*. In other words, electric charge is conserved. This law is particularly useful when applied at a position where the current is split into

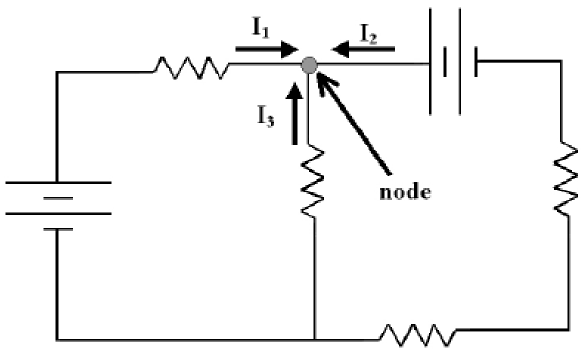


Figure 4.1: Current node in a circuit network

pieces by several wires. The point in the circuit where the current splits is known as a node. Figure 4.1 illustrates a node in a typical circuit. This relationship can be expressed mathematically

$$\sum I_{in} = \sum I_{out} \tag{4.1}$$

3.2 Kirchhoff's Voltage Law:

The algebraic sum of the voltages around any closed path is zero. Stated another way: The voltage drops around any closed loop must equal the applied voltages. This law is sometimes called the *loop rule*.

$$\sum V_i = 0 \tag{4.2}$$

Kirchhoff's Laws can be related to conservation of energy and charge if we look at a circuit with one load and source. Since the load consumes all of the power provided from the source, energy and charge are conserved. Since voltage and current can be related to energy and charge, then Kirchhoff's Laws restate the laws governing energy and charge conservation.

In order to sum the voltages around a loop, the voltage polarity of each object must be known. For a battery, the polarity is usually indicated on the battery with a "+" or "-" near one of the terminals. On a circuit diagram, the different terminals are represented by the size of the plate. The larger plate indicates a positive terminal, while a smaller plate indicates a negative terminal. When going around a loop, the sign we end up on as we go across the battery is the polarity of the battery in the loop. Figure 4.2 illustrates this convention.

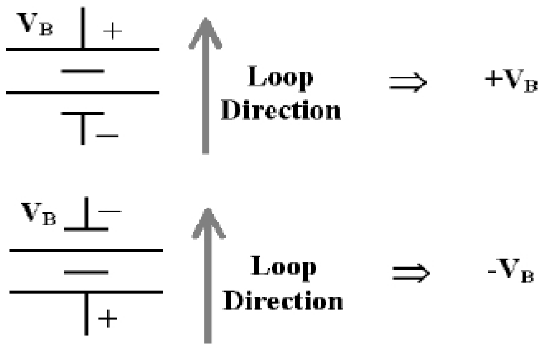


Figure 4.2: Battery voltage polarity convention

The direction of current flow through a resistor determines the polarity of resistors in a circuit.

For these types of problems, current is thought to be the flow of positive charges.
In actuality negatively charged electrons flow, but this was not known when Kirchhoff made his discovery. The discrepancy here does not affect the results, but should be kept in mind. If we consider the current to be made up of positive charges flowing through the wires, then the charges will move from higher, "+", potential to lower, "-", potential.
Just as in batteries, the sign we end up on as we go around the loop will determine the polarity of the resistor. This convention is illustrated in Figure 4.3:

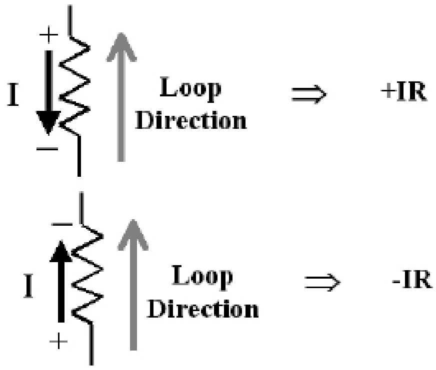


Figure 4.3: Resistor voltage polarity convention

In this set of experiments, Kirchhoff voltage and current laws will be experimentally verified for a typical circuit containing two loops. Additionally, Kirchhoff's laws will be applied to solve for the currents in a number of different circuits, and these current values will be compared to experimentally measured values.

----- End of Theory-----

4. EXPERIMENT

4.1 Setup - Procedure

1. Connect the circuit shown in Figure 4.1 using any of the resistors you have except the 10 Ω one. Use Figure 4.2 as a reference along with 4.1 as you record your data. Record the resistance values in the table 4.1 below. With no current flowing (the battery disconnected), measure the total resistance of the circuit between points A and B.

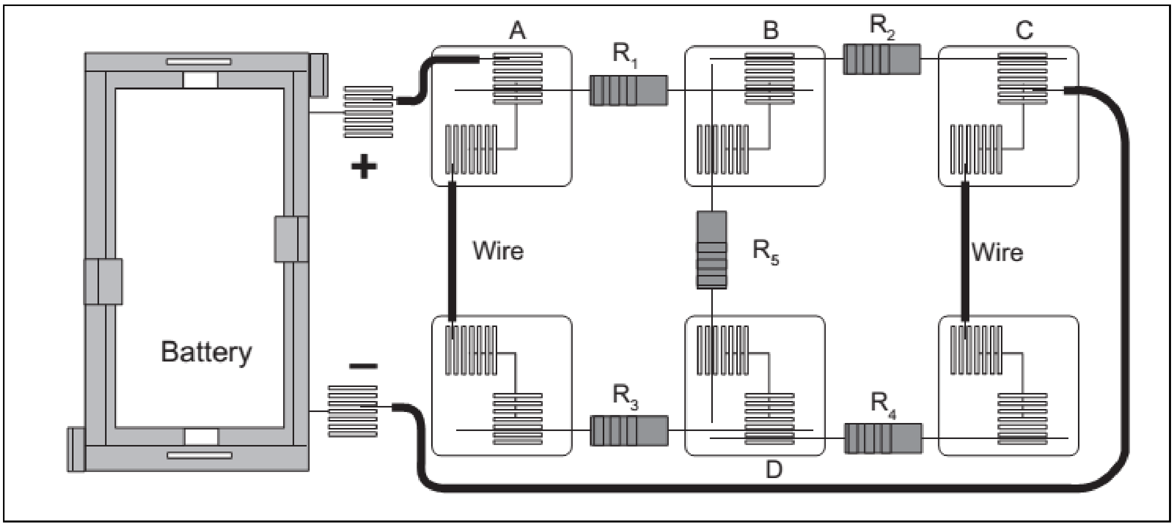


Figure 4.1

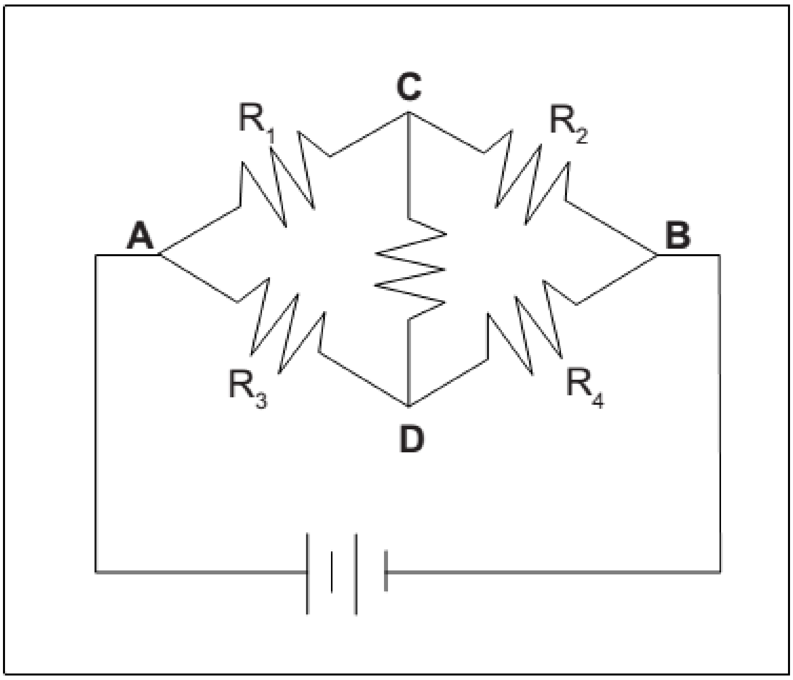


Figure 4.2

2. With the circuit connected to the battery and the current flowing, measure the voltage across each of the resistors and record the values in the table below. On the circuit diagram in Figure 4.2, indicate which side of each of the resistors is positive relative to the other end by placing a “+” at that end.
3. To measure the voltage across each of the five resistors, put one voltage lead at each end of the resistor (for example, touching the spring clips at each end). The red voltage lead represents “positive” and the black voltage lead represents “negative”. Remember to read the procedure before you begin. Data recording is easier if one person handles the sensors and the circuit and a second person operates the computer and records the data.
4. Now measure the current through each of the resistors. To do this, you have to interrupt the circuit and place the DMM in series to obtain your reading. Make sure you record each of the individual currents, as well as the current flow into or out of the main part of the circuit, I_T.
5. Record voltage values in the Table 4.1 and in the diagram.

Table 4.1

Resistance, Ω	Voltage, volts	Current, mA
R_1	V_1	I_1
R_2	V_2	I_2
R_3	V_3	I_3
R_4	V_4	I_4
R_5	V_5	I_5
R_T	V_T	I_T

4.2 Analyzing the Data

1. Determine the net current flow into or out of each of the four “nodes” in the circuit.
2. Determine the net voltage drop around at least three (3) of the six or so closed loops. Remember, if the potential goes up, treat the voltage drop as positive (+), while if the potential goes down, treat it as negative (-).

4.3 Discussion

Use your experimental results to analyze the circuit you built in terms of Kirchhoff’s Rules.

Be specific and state the evidence for your conclusions.

4.4 Extension

Build the circuit below and apply the same procedure you used previously. Analyze it in terms of Kirchhoff's Rules. If possible, try to analyze the circuit ahead of time and compare your measured values with the theoretically computed values.

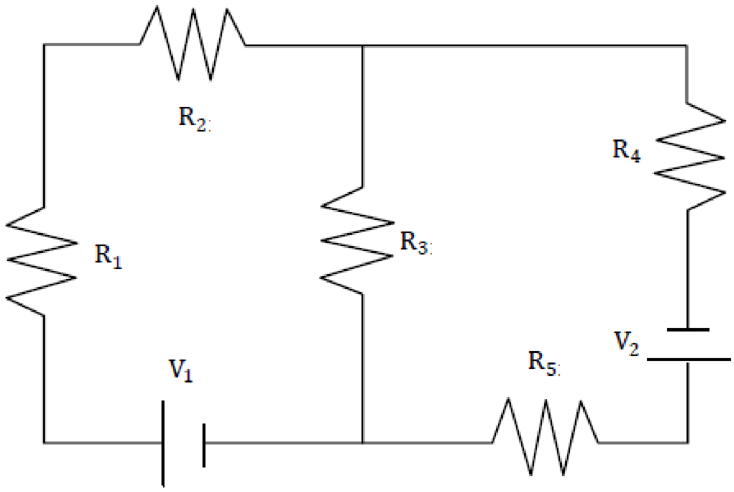


Figure 4.4: Extension

LAB 5: RC CIRCUIT

1. EQUIPMENT

INCLUDED		
1	AC/DC Electronics Laboratory	EM- 8656
1	Voltage Sensor	CI-6503
2	Banana Plug (5-pack)	SE-9750
1	Alligator Clip Adapters (10-Pack)	SE-9756
NOT INCLUDED, BUT REQUIRED		
1	ScienceWorkshop 750 Interface	CI-7650
1	DataStudio Software	

2. INTRODUCTION

The purpose of this activity is to measure the voltage across a capacitor as it is charged and then discharged through a resistor that is in series with the capacitor and the battery. A Voltage Sensor is used to measure the voltage across the capacitor. The “Output” feature of the interface is used as a DC voltage source. The experimental process will allow to measure capacitance and time constants.

3. THEORY

3.1 Exponential Charge and Discharge

When a DC voltage source is connected across an uncharged capacitor, the rate at which the capacitor charges up decreases as time passes. At first, the capacitor is easy to charge because there is very little charge on the plates. But as charge accumulates on the plates, the voltage source must “do more work” to move additional charges onto the plates because the plates already have charge of the same sign on them. As a result, the capacitor charges exponentially, quickly at the beginning and more slowly as the capacitor becomes fully charged. The charge on the plates at any time is given by:

$$q = q_{max}\left(1 - e^{-t/\tau}\right) \qquad (5.1)$$

where q_{max} is the maximum charge on the plates and τ is called the ***time constant*** and is given by $\tau = RC$. For a capacitor, the voltage across the plates is directly proportional to the amount of charge on the plates, since $q = CV$. The voltage across the plates of the capacitor will also increase exponentially as the capacitor accumulates charge. The voltage goes from zero to a maximum value V_{max}:

$$V\,(\mathrm{t}) = V_{max}\left(1 - e^{-t/\tau}\right) \qquad (5.2)$$

When the capacitor is disconnected from the voltage source and it is allowed to discharge, the charge on the plates, and thus also the voltage across the plates, decreases exponentially. The voltage drops from its value at time moment the discharge started (V_0)down to zero:

$$V\,(\mathrm{t}) = V_0 e^{-t/\tau} \qquad (5.3)$$

3.2 The Time Constant τ and the Half Life $t_{1/2}$

A certain time after the capacitor begins charging, the charge on the plates will have increased to a value that is exactly ½ of the total possible maximum charge. The time needed to reach this state is called the half-life of the circuit. The half-life and the time constant are easily related:

$$\boxed{t_{1/2} = \tau \ln 2 = RC \ln 2} \qquad (5.4)$$

Notice that at the time the capacitor is ½ charged, the voltage across the plates has also increased to ½ its maximum possible value:

$$V\,(t_{1/2}) = V_{max}\left(1 - e^{-\tau \ln 2/\tau}\right) = V_{max}\left(1 - e^{-\ln 2}\right) = \frac{1}{2} V_{max}\,.$$

3.3 Charging for One Time Constant

Let $t = 0$ be the time when the charge was $q = 0$ and the capacitor started charging. After a time of one time constant has passed, the voltage across the plates is:

$$V = 0.63\, V_{max} \qquad (5.5)$$

3.4 Discharging for One Time Constant

Let $t = 0$ be the time when the charge was $q = 0$ and the capacitor started discharging. After a time of one time constant has passed, the voltage across the plates is:

$$V = 0.37\, V_{max} \qquad (5.6)$$

3.5 The Time to Fully Charge the Capacitor

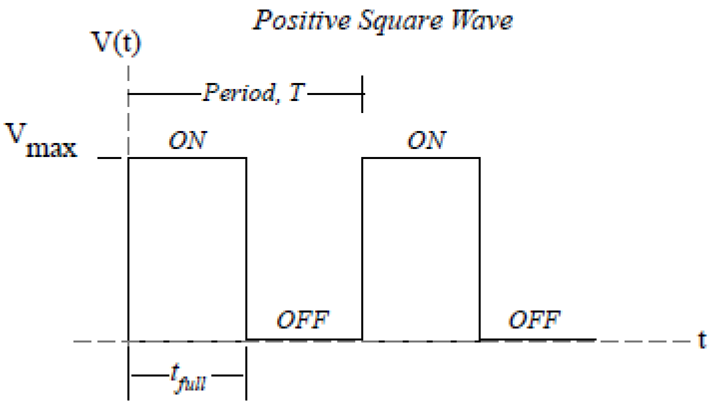
When is a capacitor charged fully? Mathematically, notice that in the expression $q = q_{max}\left(1 - e^{-t/\tau}\right)$, $q = q_{max}$ only when $t \to \infty$. Theoretically, this means that the capacitor is never fully charged! For experimental purposes, however, let's say that the capacitor will be considered to be fully charged when $q = 0{,}9999\, q_{max}$ (just applied for this experiment). How long a time would this take?

$$\boxed{t_{full} \approx 9\tau} \qquad (5.7)$$

The capacitor can be considered "fully charged" after about nine time constants.

3.6 The Positive Square Voltage Wave

A positive square voltage wave has the shape shown in the next diagram. The signal turns the voltage "ON" and "OFF" with a fixed frequency. In order to completely charge a capacitor, the signal needs to stay "ON" for at least the time full t (about nine time-constants). The period of the wave, then, needs to be twice the time to fully charge. The required frequency of the signal must then be:



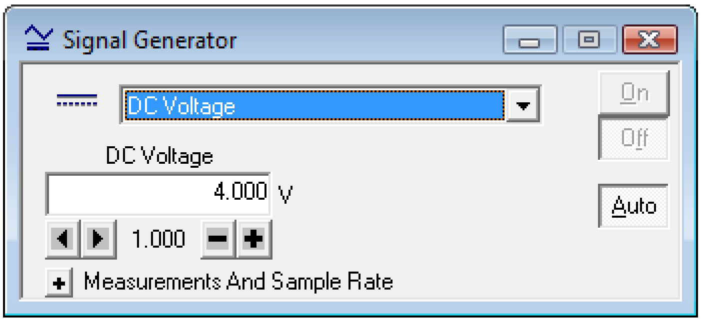
$$f = \frac{1}{T} = \frac{1}{2t_{full}} \approx \frac{1}{18\tau} \tag{5.8}$$

-------------- End of Theory-------------------

4. EXPERIMENT

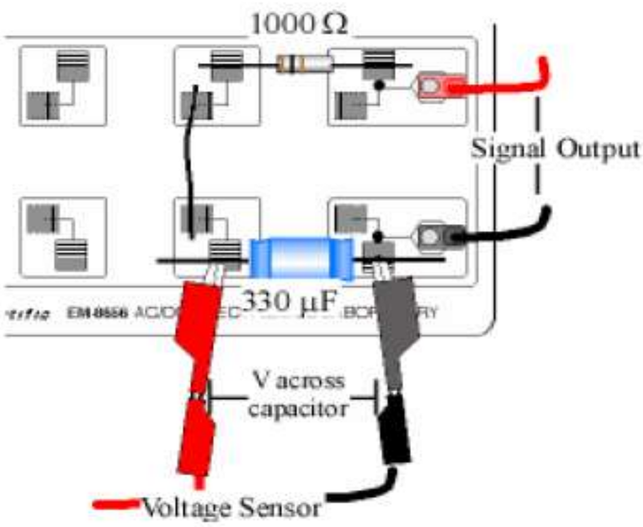
4.1 Equipment Setup

1. Connect the Voltage Sensor to the interface. Connect banana plug patch cords into the "OUTPUT" ports on the PASCO 750 Interface.
2. Open the DataStudio file: **RC Circuit.ds**. The file opens with a Graph display of voltage versus time and a Signal Generator window for controlling the output signal from the interface.



- The Signal Generator is initially set to output a 4-volt DC continuous signal.
- The Signal Generator is set to "Auto" so it will start and stop automatically when you start and stop measuring data.
- Data recording is set to stop automatically after 15 seconds.

3. Set up the circuit shown in this illustration. For the first run, use a 1000-ohm resistor (brown, black, red) and a 330 microfarad (µF) capacitor. The Voltage sensor is connected across the capacitor. The signal comes from the OUTPUT of the ScienceWorkshop Interface.

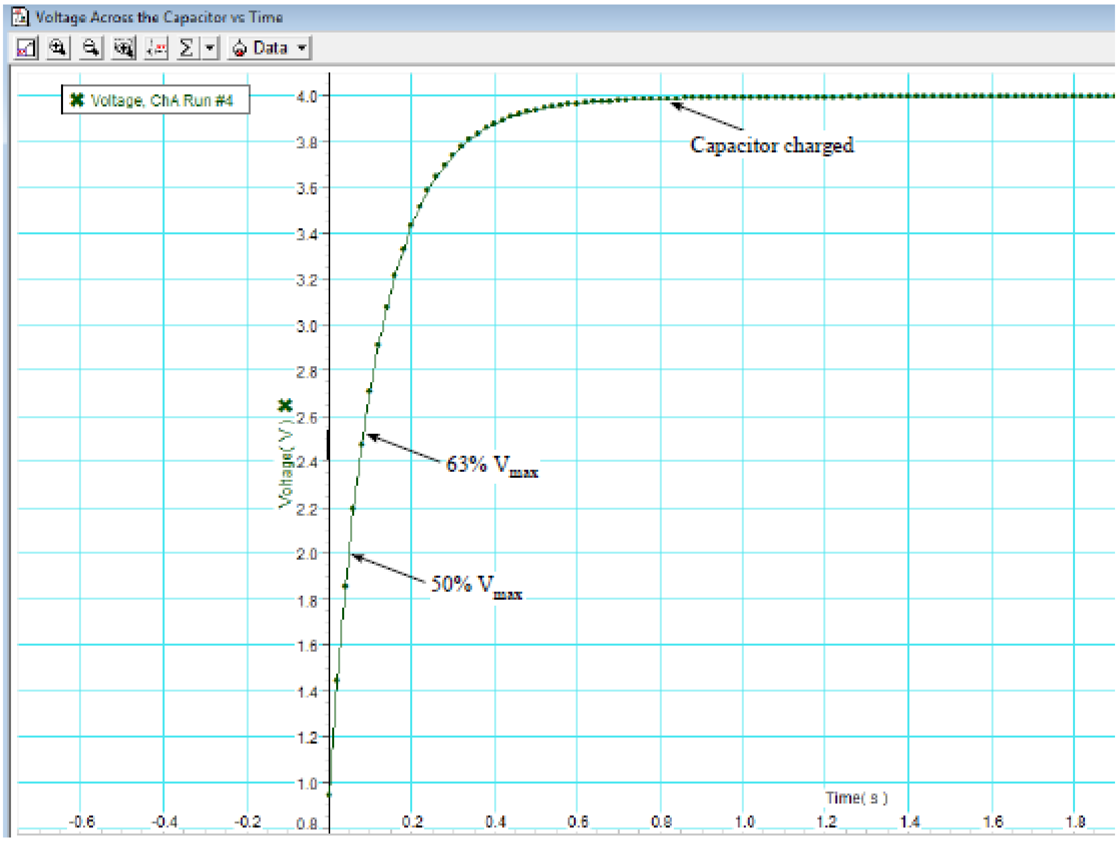


4.2 Procedure

4.2.1 Charging the Capacitor

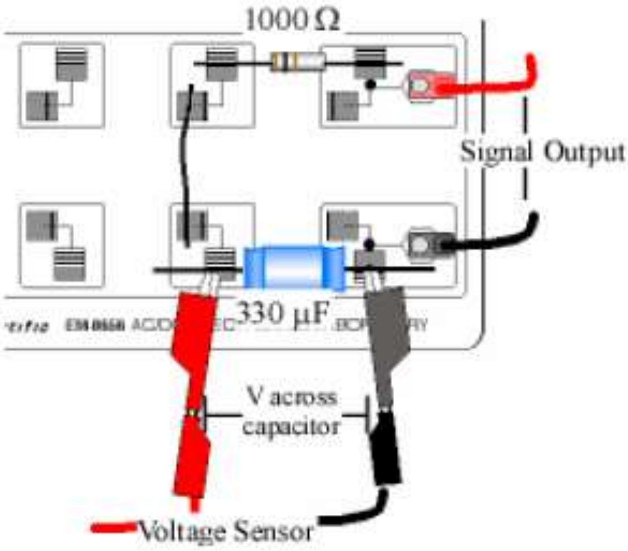
1. Click "Start" to record data for the 1000-Ω resistor. Data recording will stop automatically in 15 seconds.
2. Repeat the experiment two more times, using different resistors, of values higher than or lower than 1000 Ω.

3. Use the "Zoom Select" and the "Smart Tool" to record the following data for each trial:
   - Time to fully charge, t_{full} (the first time voltage reached its maximum value)
   - Time to reach ½ of V_{max} (this is the half-life,$t_{1/2}$)
   - Time to reach 63% of V_{max} (this is the experimental time constant, τ_{exp})
4. Use the measured half-life and Eq. 5.3 to calculate another experimental value for the time constant.
5. Use the measured time to fully charge and Eq. 5.6 to calculate a third experimental value for the time constant.
6. Repeat the experiment with different resistors.
7. Compare the experimental values to the theoretical values by calculating percent errors.

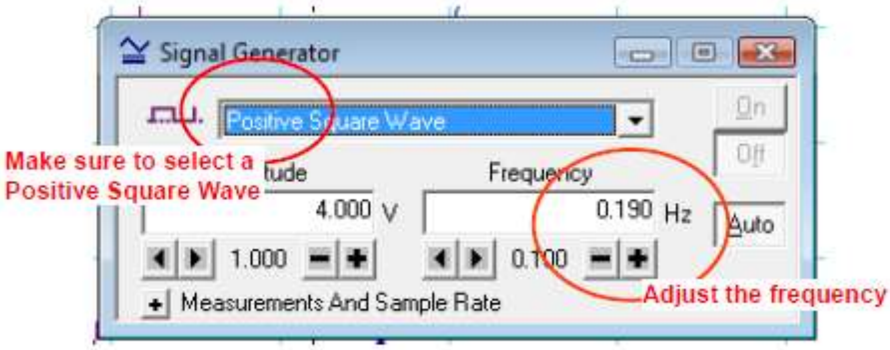


4.2.2 Discharging the Capacitor

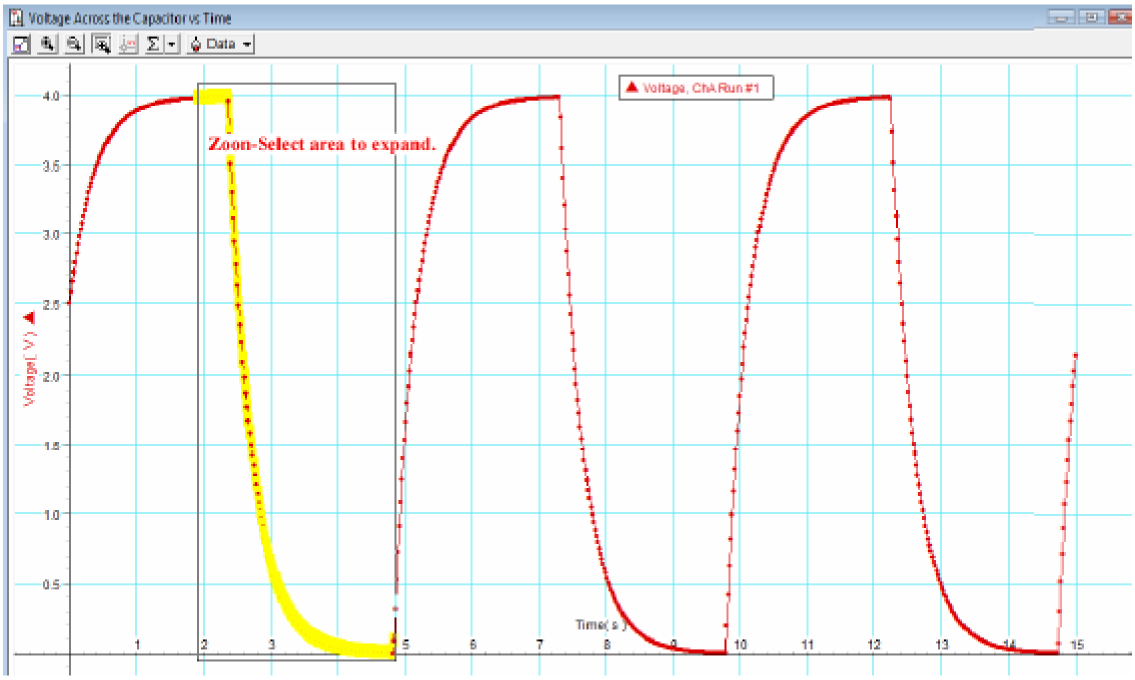
1. Set the circuit as illustrated, using a 1000 Ω resistor and a 330 µF capacitor
2. Use Eq. 5.8 to calculate the required frequency of the signal.



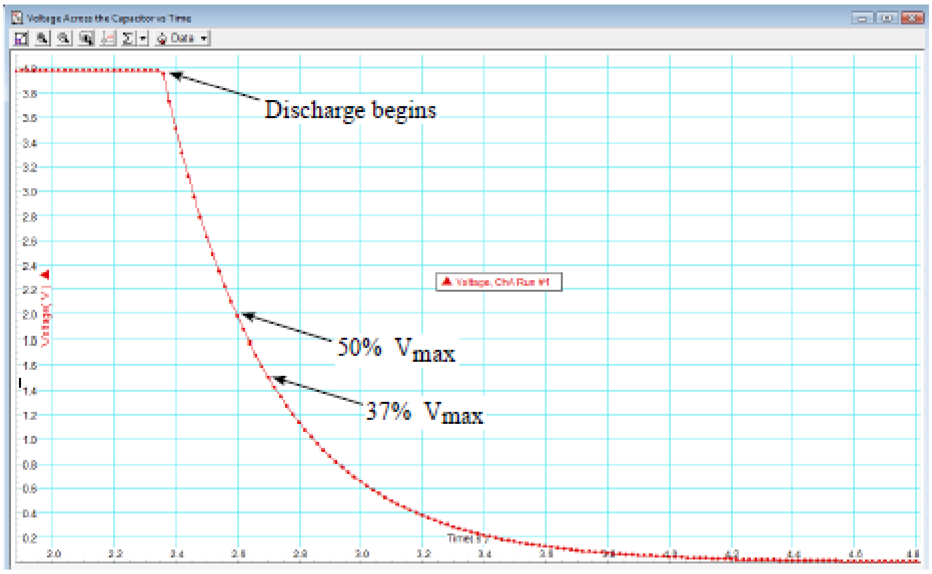
3. In DataStudio: In the Window menu, choose the Signal Generator.
4. Change the signal to a "Positive Square Wave" and adjust the frequency according to your calculation.



5. Click "Start" to record data. Data recording will stop automatically in 15 seconds.
6. Use the "Zoom Select" tool of the graph toolbar to click-and-draw a rectangle over a region of the plot that shows the voltage decreasing from its maximum value to zero.
7. Use the graph tools to exactly find the time at which this cycle of discharging started. Record it as t_0 in the data table.
8. Find the first time after t_0 at which the voltage was 37% of V_{max}. Record it as t in the data table.
9. Repeat the experiment with different resistors. Do not forget to adjust the frequency of the signal.



10. Calculate the experimental time constant of each case and compare to the theoretical values by determining percent errors.



LAB 6: LR CIRCUIT

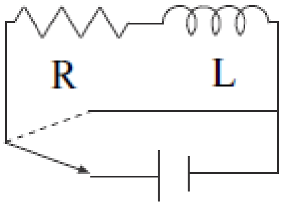
1. EQUIPMENT

INCLUDED		
1	Voltage Sensor	CI-6503
1	Multi-meter	SE-9786
2	Patch Cords	SE-9750
1	Inductor coil and Iron Core	
1	Resistor, 10 ohm	
2	Wire Lead	
NOT INCLUDED, BUT REQUIRED		
1	ScienceWorkshop 750 Interface	CI-7599
1	DataStudio Software	

2. INTRODUCTION

What is the relationship between the voltage across the inductor and the voltage across the resistor in an inductor-resistor circuit? What is the relationship between the current through the inductor and the behavior of an inductor in a DC circuit?

3. THEORY



When a DC voltage is applied to an inductor and a resistor in series a steady current will be established:

$$I_{max} = \frac{V_0}{R} \quad (6.1)$$

where V_0 is the applied voltage and R is the total resistance in the circuit.

But it takes time to establish this steady-state current because the inductor creates a back-emf in response to the rise in current. The current will rise exponentially:

$$I = I_{max}\left(1 - e^{-(R/L)t}\right) = I_{max}\left(1 - e^{-t/\tau}\right) \quad (6.2)$$

where L is the inductance and the quantity $\frac{L}{R} = \tau$ is the inductive time constant. The inductive time constant is a measure of how long it takes the current to be established. One inductive time constant is the time it takes for the current to rise to 63% of its maximum value (or fall to 37% of its maximum). The time for the current to rise or fall to half its maximum is related to the inductive time constant by

$$t_{1/2} = \tau \ln 2 \qquad (6.3) \qquad\qquad \tau = \frac{t_{1/2}}{\ln 2} \qquad (6.4)$$

Since the voltage across a resistor is given by $V_R = IR$, the voltage across the resistor is established exponentially:

$$V_R = V_0\,(1 - e^{-t/\tau}) \qquad (6.5)$$

Since the voltage across an inductor is given by $V_L = L\left(\frac{dI}{dt}\right)$, the voltage across the inductor starts at its maximum and then decreases exponentially:

$$V_L = V_0\, e^{-t/\tau} \qquad (6.6)$$

After a time t≫ τ, a steady- state current I_{max} is established and the voltage across the resistor is equal to the applied voltage, V_0 . The voltage across the inductor is zero. If after the maximum current is established, the voltage source is turned off, the current will then decrease exponentially to zero while the voltage across the resistor does the same and the inductor again produces a back-emf which decreases exponentially to zero. In summary:

DC Voltage applied	DC Voltage turned off
$I = I_{max}\,(1 - e^{-t/\tau})$	$I = I_{max}\, e^{-t/\tau}$
$V_R = V_0\,(1 - e^{-t/\tau})$	$V_R = V_0\, e^{-t/\tau}$
$V_L = V_0\, e^{-t/\tau}$	$V_L = -V_0\, e^{-t/\tau}$

At any time, Kirchhoff's Loop Rule applies: The algebraic sum of all the voltages around the series circuit is zero. In other words, the voltage across the resistor plus the voltage across the inductor will add up to the source voltage.

For You To Do

Use the 'Output' feature of the *ScienceWorkshop* interface to provide voltage for a circuit consisting of an inductor and a resistor. (The interface produces a low frequency square wave that imitates a DC voltage being turned on and then turned off.) Use Voltage Sensors to measure the voltages across the inductor and resistor.

Use *DataStudio* to record and display the voltages across the inductor and resistor as the current is established exponentially in the circuit. Use the graph display of the voltages to investigate the behavior of the inductor-resistor circuit.

------------- End of Theory------------------

4. EXPERIMENT

4.1 Computer Setup

1. Connect the *ScienceWorkshop* interface to the computer, turn on the interface, and turn on the computer.
2. Connect one Voltage Sensor to Analog Channel A. This sensor will be “Voltage Sensor A”. Connect the second Voltage Sensor to Analog Channel B. This sensor will be “Voltage Sensor B”.
3. Connect banana plug patch cords into the ‘OUTPUT’ ports on the interface.
4. Open the document titled LR Circuit.ds

- The *DataStudio* document opens with a Graph display of voltage versus time for the ‘Output, the resistor, and the inductor. The document also has a Workbook display. Read the instructions in the Workbook.
- The Signal Generator is set to output a ‘positive-only’ square wave at 3.00 volts and 50.00 Hz. The Signal Generator is set to ‘Auto’ so it will start and stop automatically when you start and stop measuring data.
- Data recording is set to automatically stop at 0.12 seconds.

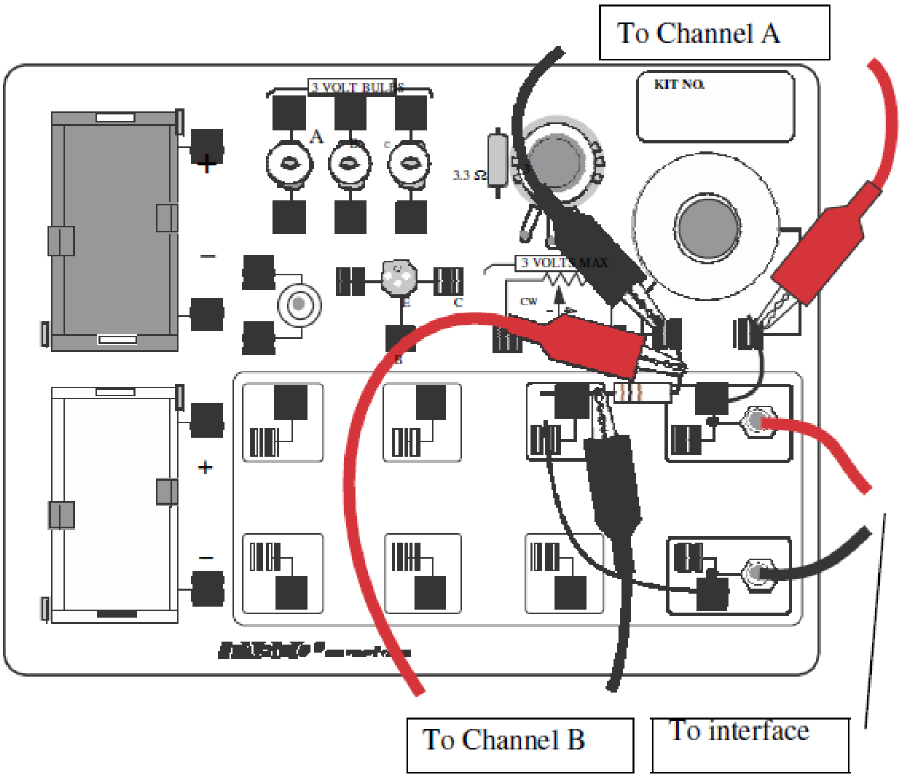
4.2 Sensor Calibration and Equipment Setup

- You do not need to calibrate the Voltage Sensor.

1. Put the iron core into the inductor coil on the AC/DC Electronics Lab circuit board.
2. Connect a 5-inch wire lead between a component spring next to the top banana jack, and the component spring at the right hand edge of the inductor coil on the circuit board.
3. Connect the 10-ohm resistor (brown, black, black) between the component spring at the left-hand edge of the inductor coil, and the second component spring to the left of the top banana jack.
4. Connect another 5-inch wire lead between the component spring nearest to the one in which one end of the 10-ohm resistor is connected, and a component spring nearest to the bottom banana jack at the lower right corner of the circuit board.
5. Put alligator clips on the banana plugs of both Voltage Sensors. Connect the alligator clips of Voltage Sensor “A” to the component springs at both sides of the inductor coil.

6. Connect the alligator clips of Voltage Sensor "B" to the wires at both ends of the 10Ω resistor.
7. Connect banana plug patch cords from the 'OUTPUT' ports of the interface to the banana jacks on the AC/DC Electronics Lab circuit board.
8. Replace 10 Ω resistor by a resistor with the value from 20 Ω to 100 Ω. Repeat steps 1-7.

4.3 Data Recording



1. Use a Multi-meter to measure the resistance of the inductor coil on the AC/DC Electronics Lab circuit board. Record the coil resistance in the Data section.
2. Use a Multi-meter to measure the resistance of the 10-ohm resistor. Record the measured resistor value in the Data section.
3. Begin measuring data. The Signal Generator will start automatically.

- Data recording will end automatically. 'Run #1' will appear in the Data list.

4.4 Analyzing the Data

- The voltage across the resistor is in phase with the current. The voltage is also proportional to the current (that is, V = IR). Therefore, the behavior of the current is studied indirectly by studying the behavior of the voltage across the resistor (measured on Channel B).

1. Use the built-in analysis tools in the Graph display to determine the time to 'half-max' voltage.

- In *DataStudio*, use the 'Smart Tool'.
- Move the cursor to the top of the exponential part of the curve where the plot of voltage across the resistor (Channel B) is at its maximum. Record the peak voltage (Y-coordinate) and the time (X-coordinate) for that point in the Data table. Determine the voltage that is half of the peak (the "half-max" voltage).
- Move the cursor down the exponential part of the plot of resistor voltage until you reach the "half-maximum" (peak) voltage. Record the X-coordinate (time) for this point.
- Subtract the time for the peak voltage from the time for the half-max voltage to get the time for the voltage to reach half-max. Record this time in the Data table.

2. Calculate the inductive time constant based on the total resistance in the circuit and the value for the inductance of the inductor coil with the iron core: L = 28 millihenry or 0.028 H. Inductive time constant, $\tau = \frac{L}{R}$
3. Record the calculated value for the inductive time constant in the Data section.

4.5 Questions

1. How does the inductive time constant found in this experiment compare to the theoretical value given by $\tau = \frac{L}{R}$? (Remember that *R* is the total resistance of the circuit and therefore must include the resistance of the coil as well as the resistance of the resistor.)
2. Does Kirchhoff's Loop Rule hold at all times? Use the graphs to check it for at least three different times: Does the sum of the voltages across the resistor and the inductor equal the source voltage at any given time?

4.6 Extension

Take the iron core in the coil out and repeat "**4.3: Data Recording**". From the relationship $\tau = \frac{L}{R}$ and $t_{1/2} = \tau \ln 2$, find the new inductance of the inductor.

LAB 7: MAGNETIC FIELDS OF COILS

1. EQUIPMENT

	INCLUDED:	
1	Helmholtz Coil Base	EM-6715
2	Field Coil (2)	EM-6711
1	Primary and Secondary Coils	SE-8653
1	Patch Cords (set of 5)	SE-9750
1	Patch Cords (set of 5)	SE-9751
1	60 cm Optics Bench	OS-8541
1	Dynamics Track Mount	CI-6692
1	20 g hooked mass (Hooked Mass Set)	SE-8759
2	Small Base and Support Rod (2)	SE-9451
2	Optics Bench Rod Clamps (2)	648-06569
1	DC Power Supply	SE-9720
1	Digital Multi-meter	SE-9786
1	Magnetic Field Sensor	CI-6520A
1	Rotary Motion Sensor	CI-6538
	NOT INCLUDED, BUT REQUIRED:	
1	ScienceWorkshop 500 or 750 Interface	CI-6400
1	DataStudio Software	CI-6870

2. INTRODUCTION

The magnetic fields of various coils are plotted versus position as the Magnetic Field Sensor is passed through the coils, guided by a track. The position is recorded by a string attached to the Magnetic Field Sensor that passes over the Rotary Motion Sensor pulley to a hanging mass.

It is particularly interesting to compare the field from Helmholtz coils at the proper separation of the coil radius to the field from coils separated at less than or more than the coil radius. The magnetic field inside a solenoid can be examined in the axial directions.

3. THEORY

When a wire carries electric current, a circular magnetic field is created around the wire. The direction of the magnetic field depends on the current one and obeys the right-hand rule. The strength of the magnetic field is proportional to the current and the position where the field is measured. The magnetic field becomes stronger near the wire, while it gets weaker when moving away from the wire. At a given position, the faster the current is, the stronger the magnetic field becomes. However, an electrical wire cannot carry any electric current. In order to create strong magnetic field, when the current is fixed, one can combine many wires carrying the electric current with the same direction into a small space, such as coil, solenoid, Helmholtz coils, etc.

In the following sections we will look at the expressions of the magnetic fields of the coils (a single coil, two coils, and solenoid) in more details.

3.1 Single Coil

For a coil of wire having radius R and N turns of wire, the magnetic field along the perpendicular axis through the center of the coil is given by

$$B = \frac{\mu_o N I R^2}{2\left(x^2 + R^2\right)^{\frac{3}{2}}}\hat{x} \qquad (7.1)$$

where

μ_0: permeability constant ($4\pi \times 10^{-7}\ \mathrm{T}\cdot\frac{\mathrm{m}}{\mathrm{A}} \approx 1.26 \times 10^{-6}\ \mathrm{T}\cdot\frac{\mathrm{m}}{\mathrm{A}} \approx 1.26 \times 10^{-2}\ \mathrm{Gauss}\cdot\frac{\mathrm{m}}{\mathrm{A}}$)

N: the number of turns of the coils

R: the radius of the coil (m)

I: The electric current running (A)

x: distant from the center of the coil (m)

$\hat{x}$: unit vector of the perpendicular axis and through the center of the coil.

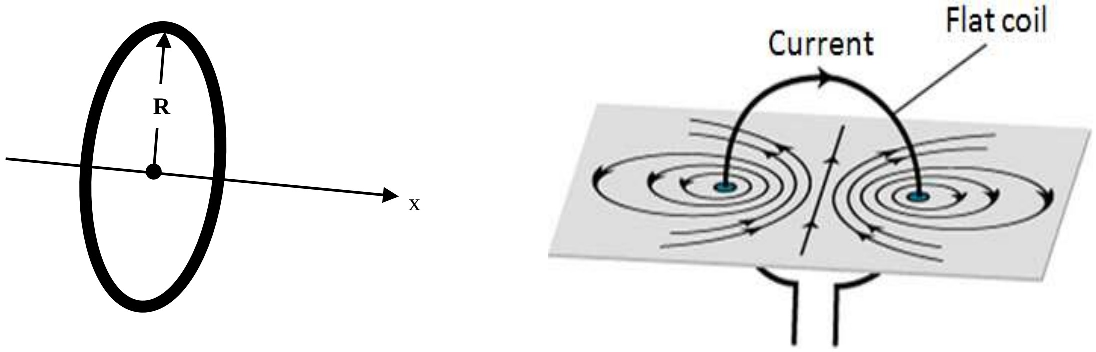


Figure 7.1: Single Coil (left) and its magnetic field lines (right)

3.2 Two Coils

In this part, a pair of conducting circular coils (Fig.7.2) is combined. The two coils are identical; they have the same number of turns *N*, radius *R*, and carry an electric current *I* in the same direction. The separation *d* between the coils and be changed. When the coils are separated by a distance equivalent to the radius of the coils, they are called Helmholtz coils.

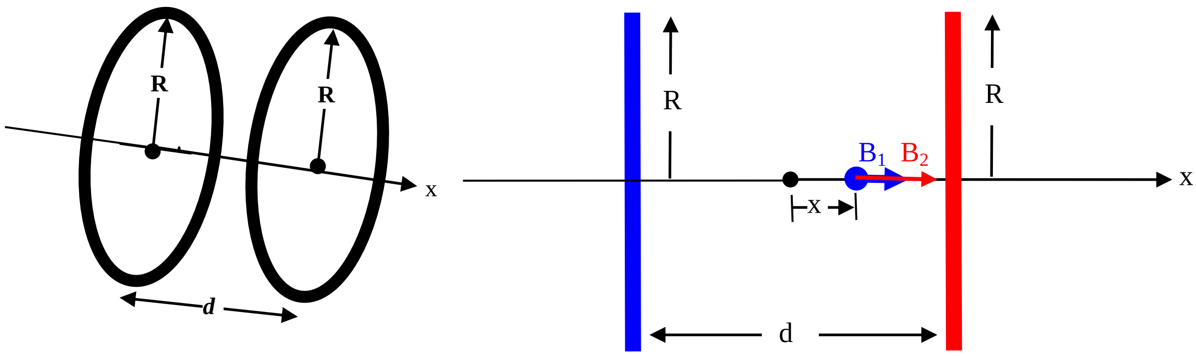


Figure 7.2: Two Coils with Arbitrary Separation

The total magnetic field $\vec{B}$ created by the coils at a position x along the perpendicular axis through the centers of the coils is the superposition of the magnetic fields generated by the two separated coils whose magnetic fields $\overrightarrow{B_1}$ and $\overrightarrow{B_2}$. The magnetic field $\vec{B}$ is given by

$$\vec{B} = \vec{B}_1 + \vec{B}_2$$
$$= \frac{\mu_o NIR^2}{2}\left(\frac{1}{\left(\left[\frac{d}{2}-x\right]^2+R^2\right)^{\frac{3}{2}}}+\frac{1}{\left(\left[\frac{d}{2}+x\right]^2+R^2\right)^{\frac{3}{2}}}\right)\hat{x} \qquad (7.2)$$

For Helmholtz coils, the coil separation d equals the radius R of the coils. This coil separation gives a uniform magnetic field between the coils. Plugging in x = 0 gives the magnetic field at a point on the x-axis centered between the two coils:

$$\vec{B} = \frac{8\mu_o NI}{\sqrt{125}R}\hat{x} \qquad (7.3)$$

The lines in Fig. 7.3 illustrate the magnetic fields created by the Helmholtz coils

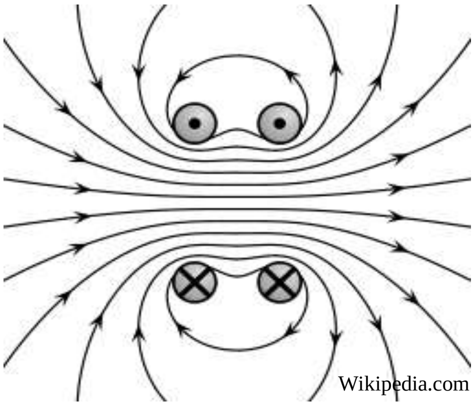


Figure 7.3: A uniform magnetic field is created by Helmholtz coils

3.3 Solenoid

A solenoid (Fig. 7.4) is a coil whose length is much longer than its diameter. Similar to the coils in the previous section, a solenoid can create magnetic field when an electric current is applied to the loop.

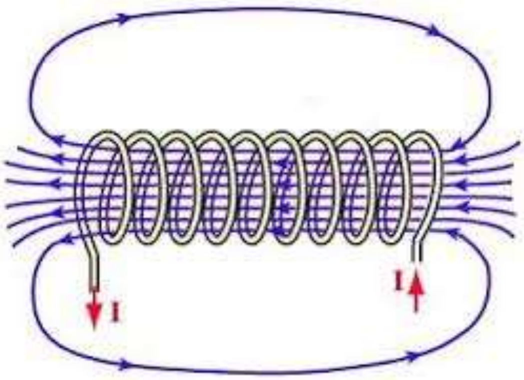


Figure 7.4: Solenoid

An ideal solenoid is a solenoid which is infinitely long and consists of very tightly turns of square wire. An important property of the ideal solenoid is that the magnetic field inside the solenoid id uniform and parallel to the solenoid axis. By using Ampere's law, the magnetic field inside the ideal solenoid can be calculated,

$$B = \mu_o n I \tag{7.4}$$

Where $n=N/L$ and I are the number of turns per unit length and the current of the solenoid, respectively.

4. EXPERIMENT

4.1 Set Up

1. Attach a single coil to the Helmholtz Base. Connect the DC power supply directly across the coil (not across the coil's internal resistor). See Figure 5.

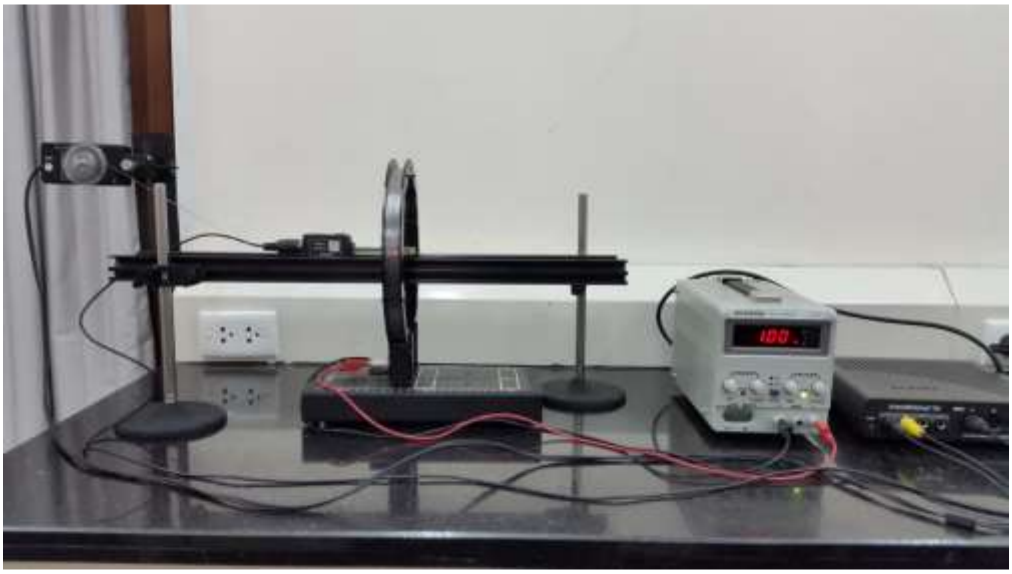


Figure 7.5: Single Coil Setup

2. Pass the optics track through the coil and support the two ends of the track with the support rods. Level the track and adjust the height so the Magnetic Field Sensor probe will pass through the center of the coil when it is pushed along the surface of the track.
3. Attach the Rotary Motion Sensor to the track using the bracket. Cut a piece of thread long enough to reach from the floor to the track. Tape one end of the thread to the side of the Magnetic Field Sensor and pass the other end of the thread over the middle step of the Rotary Motion Sensor pulley and attach the 20-g mass. Place the Magnetic Field Sensor in the center of the track and adjust the position of the Rotary Motion Sensor so the thread is aligned with the middle step pulley.
4. Plug the Magnetic Field Sensor into Channel A of the ScienceWorkshop 750 interface. Plug the Rotary Motion Sensor into Channels 1 and 2. Note that the Rotary Motion Sensor plugs can be reversed in Channels 1 and 2 to change which direction of rotation is positive.
5. Turn on the DC power supply and adjust the voltage so about 1 Amp flows through the coil.
6. Open the DataStudio program called "Magnetic Field of Coils.ds".

4.2 Single coil procedure

1. Set the Magnetic Field Sensor switch on Axial and x10 gain. With the DC power supply off, set the Magnetic Field Sensor in the middle of the track about 25 cm from the coil. Press the tare button. Turn on the DC power supply.
2. Click on START in DataStudio and slowly move the Magnetic Field Sensor along the center of the track, keeping the probe parallel to the track, until the end of the sensor is about 25 cm past the coil. Then click on STOP.
3. Use the Smart Tool on the graph to measure the position of the peak. Click on the DataStudio calculator and enter the peak position in for the constant (d) in the equation for the distance. This will center the peak on zero on the graph.
4. Click on FIT at the top of the graph and choose User-Defined Fit. Type in the theoretical equation for the magnetic field and enter in the current, the coil radius, and number of turns in the coil (N=200).
5. Does the theoretical equation fit everywhere? If not, why not?

4.3 Two coils procedure

1. Attach a second coil to the Helmholtz Base at a distance from the other coil equal to the radius of the coil. Make sure the coils are parallel to each other. See Figure 7.6.

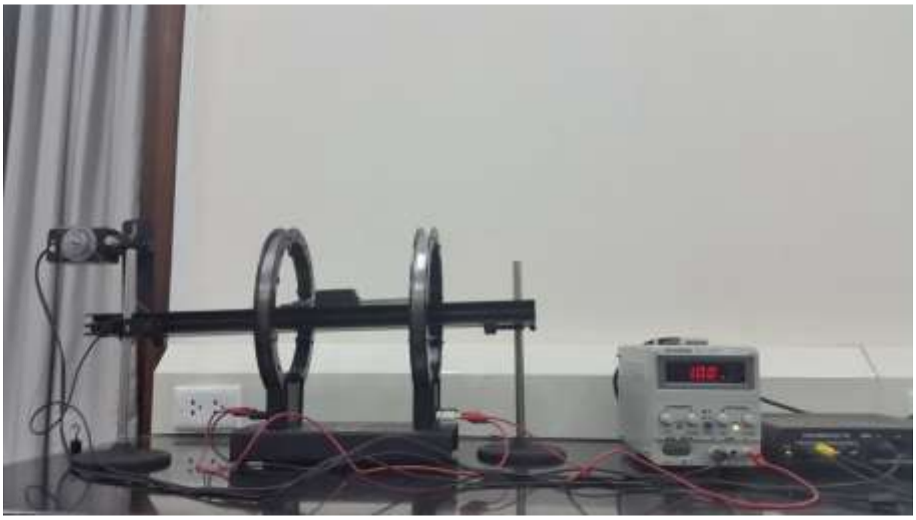


Figure 7.6: Two Coils Setup

2. Connect the second coil in series with the first coil. See Figure 7.7.
3. Set the Magnetic Field Sensor switch on Axial and x10 gain. With the DC power supply off, set the Magnetic Field Sensor in the middle of the track about 15 cm from the first coil. Press the tare button.

4. Turn on the DC power supply. Click on START in DataStudio and slowly move the Magnetic Field Sensor along the center of the track, keeping the probe parallel to the track, until the end of the sensor is about 15 cm past the second coil. Then click on STOP.

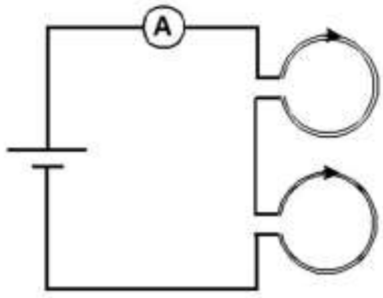


Figure 7.7: Two coils Wiring

5. Use the Smart Tool on the graph to measure the position of the center of the peak. Click on the DataStudio calculator and enter the peak position in for the constant (d) in the equation for the distance. This will center the peak on zero on the graph.
6. Click on the annotation button at the top of the graph and put a note showing the position of each coil on the graph. Is the magnetic field strength constant between the coils?
7. Calculate the theoretical value for the magnetic field between the coils and compare it to the measured value on the graph.
8. Now change the separation between the coils to 1.5 times the radius of the coils. Repeat steps 3 through 6.
9. Now change the separation between the coils to half the radius of the coils. Repeat steps 3 through 6.

4.4 Solenoid procedure

1. Connect the DC power supply in series with the solenoid.

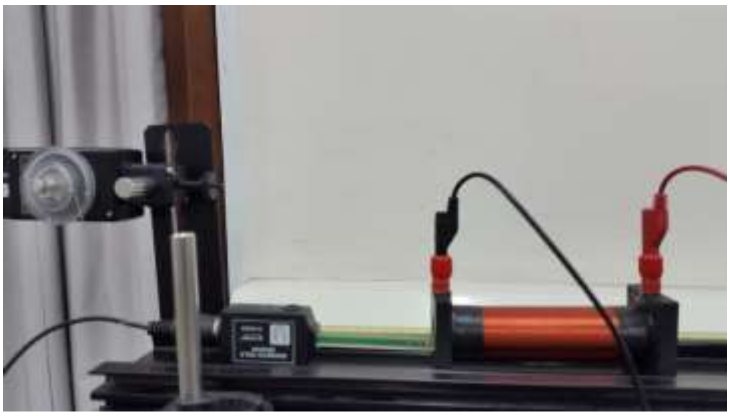


Figure 7.8: Solenoid Setup

2. Set the Magnetic Field Sensor switch on Axial and x10 gain. With the DC power supply off, put the Magnetic Field Sensor outside the solenoid (see Figure 8). Press the tare button.

3. Turn on the DC power supply and adjust the current to 100 mA.
4. Click on START and move the magnetic field sensor from outside to inside to examine the magnetic field at various points inside the solenoid, keeping the sensor probe parallel to the long axis of the solenoid.
5. Is the field inside the solenoid constant? What happens near the end of the solenoid?
6. Measure the length of the coil and using the given number of winds in the coil (N=2920), calculate the theoretical value of the magnetic field. Compare this value to the value at the center at the coil.
7. Is the field inside the solenoid constant? What happens near the end of the solenoid?

LAB 8: ELECTRON CHARGE TO MASS RATIO EXPERIMENT

1. EQUIPMENT

1	e/m apparatus	SE-9638
1	Power Supply	SF-9584B
1	High Voltage Power Supply	SF-9585A
2	Banana plug patch cords red	such as SE-9750
2	Banana plug patch cords black	such as SE-9751

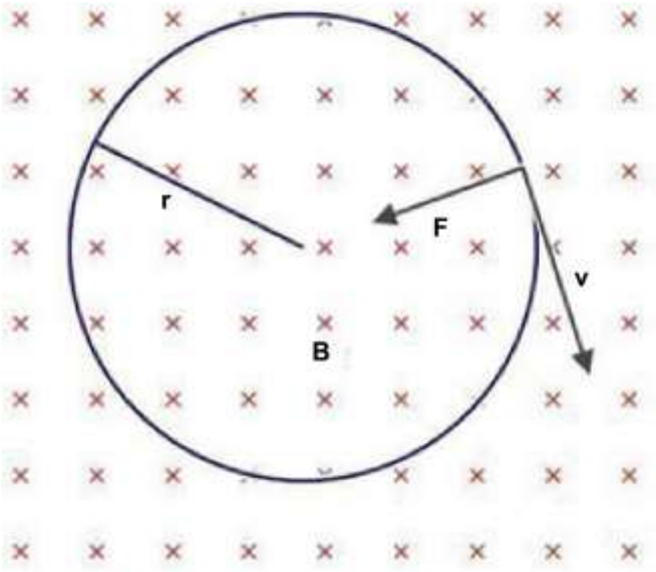
2. INTRODUCTION

The e/m apparatus (Electron Charge-to-Mass Ratio) provides a simple method for measuring e/m, the charge to mass ratio of the electron. The method is similar to that used by J.J. Thomson in 1897. A beam of electrons is accelerated through a known potential, so the velocity of the electrons is known. A pair of Helmholtz coils produces a uniform and measurable magnetic field at right angles to the electron beam. This magnetic field deflects the electron beam in a circular path.

3. THEORY

In 1887, J. J. Thomson showed that the mysterious cathode rays were actually negatively charged particles — he had discovered the electron. In the same year he measured the specific charge (e/m) of the cathode ray particles, providing the first measurement of one of the fundamental constants of the universe. The specific charge is defined as the charge per unit mass of the particle. Thomson discovered that the value of e/m was independent of the gas used and also independent of the nature of the electrodes.

In the e/m tube, the electrons move along a circular path in a uniform magnetic field. The tube contains helium gas at a precisely set pressure. The gas atoms are ionized along the length of the circular path due to collisions with electrons. As a result, they are excited and emit light, thereby indirectly making the circular path of the electrons visible. The radius of the path can then be measured directly with a ruler. Since the accelerating voltage U of the electron gun and the magnetic field B are known, it is possible to calculate the specific charge of an electron e/m from the radius of the circular path r.



An electron moving with velocity (**v**) in a direction perpendicular to a uniform magnetic field (**B**) experiences a Lorentz force (**F**) in a direction perpendicular to both the velocity and the magnetic field, **F = e•v•B**

where e is the charge on an electron.

This gives rise to a centripetal force on the electron in a circular path with radius (**r**), where F = m·v2/r, and m is the mass of an electron.

Thus **e·B·r = m·v.** The velocity (**v**) depends on the accelerating voltage (**U**) of the electron gun: **v2 = 2•U•e/m**. Therefore, the specific charge of an electron is given by:

$$\frac{e}{m} = \frac{2U}{B^2 r^2}$$

If we measure the radius of the circular orbit in each case for different accelerating voltages **U** and different magnetic fields **B**, then, according to equation, the measured values can be plotted in a graph of $\mathbf{B^2 r^2}$ against **2U** as a straight line through the origin with slope **e/m**.

4. EXPERIMENT

4.1 Adjust Operating Voltages and Current

Note:

- Before switching on the power, be sure that all voltage and current controls are turned fully counterclockwise.

- To get a clearer view of the electron beam, conduct the experiment in a darkened room.

1. Connect all the cables and cords as described previously.

2. For both power supplies, push in the Power Switch to the ON position.
3. On AC voltage Power Supply, set the Voltage Range Switch to 4 V. Wait several minutes for the filament to heat up*. When it does, you will see the electron beam emerge from the electron “gun”. The electron beam is initially horizontal and is visible as a dim, bluish ray.
4. On the Tunable DC Power Supply, set the Accelerating Voltage (anode) to lower than 100 V DC.
5. On Power Supply II, adjust the voltage output to the Accelerating Voltage to optimize the focus and brightness of the electron beam.
6. On the Tunable DC Power Supply, increase the current to the Helmholtz coils which is not exceed 9 V and 1.5 A. Watch the electron beam and check that the electron beam curves upward.
7. Continue increasing the current until the electron beam forms a closed circle.

4.2 Record Data: Standalone

8. Carefully read the Current Display to find the current ($\boldsymbol{I_H}$) through the Helmholtz coils and record the value in Table 1.8. Carefully read the Voltmeter and record the Acceleration Voltage ($\boldsymbol{U}$) in Table 1.8.
9. Carefully measure the radius, ***r***, of the electron beam. Look through the e/m tube at the Mirrored Scale. To avoid parallax errors, move your head to align the electron beam in the tube with the reflection of the beam as you see it in the Mirrored Scale. Measure the radius of the electron beam as you see it on both sides of the Mirrored Scale, and then average the results. Record the average radius in Table 1.8.
10. Record other series of measured values for different Accelerating Voltages ($\boldsymbol{U}$) and current ($\boldsymbol{I_H}$) through the Helmholtz coils. Record your measurements in Table 1.8.

4.3 Analysis of e/m Measurements

The magnetic field, **B**, generated in a pair of Helmholtz coils is proportional to the current, $\mathbf{I_H}$, passing through a single coil. The constant of proportionality, **k**, can be determined from the coil radius, **R**, and the number of turns, **N**, on the coil.

$$B=\frac{\left(\frac{4}{5}\right)^{3/2}\mu_0 N I_H}{R}$$

With this expression for **B**, the initial formula for e/m,

$$\frac{e}{m} = \frac{2U}{B^2 r^2}$$

becomes:

$$\frac{e}{m} = 2U \frac{\left(\frac{5}{4}\right)^3 R^2}{\left(N\mu_0 I_H r\right)^2}$$

R = 158 mm and N = 130 turns per coil (Radius of the Helmholtz coils)

U = Acceleration Voltage

N = Number of turns on each coil

μ_0 = Permeability constant ($4\pi \times 10^{-7}$)

I_H = Current through the Helmholtz coils

r = Radius of the electron beam (closed circle)

Accepted value of the charge-to-mass ratio, e/m, is 1.76×10^{11} C/kg