Lab Manual for General Physics II - 10164

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Lab report

You must hand in a typed lab report for every lab you perform. The lab report must include the following:

- 1. Type your name, date, the day of the week you did the lab, and the name of the TA. (5 points)
- 2. Introduction (15 points): The introduction should include a general overview of the experiment, the goal of the experiment, what you expect to find and the theory behind the experiment. Summarize the whole point of doing the lab. Your introduction should be about one page long.
- 3. Results (20 points): Present the data in the form of a table or a graph. Usually you will give details of what you observed in the lab. If you deviated from the instructions in the manual, explain you method. Only important information pertinent to the lab should be presented. Show examples of any calculations carried out including estimates of the error. Remember to include units.
- 4. Discussion/Conclusion (40 points): Discuss in your own words and from your point of view your results. Example: Looking at your results, tables or graph, can you see any general trend? What is the behaviour of the graph/line? What was the aim of the experiment? Have we achieved anything? If not, how large is the error? Does your result make sense? Can you compare your result to those from the books? What does the book say? Be sure to answer any questions asked in the lab manual. Of course, any additional requests or instructions by the TA must be addressed in the report.

Lab 1 Electric Field Mapping

1.1 Introduction

For macroscopic objects with electrical charges distributed throughout the volume, the calculations of the electrostatic forces from the Coulomb's formula is difficult. Therefore, it is useful to describe the interaction forces as a product of the charge, q, and the electric field intensity, E.

$$F = qE. \tag{1.1}$$

As seen from the above equation, the knowledge of the electric field enables calculations of the electrostatic forces. An electric field can be found by analyzing the map of the electric field lines. The electric field lines, also called the lines of forces, originate on and are directed away from positive charges, and end on and are directed toward negative charges. The electric field lines enable one to find the direction of the vector \vec{E} ; the vector \vec{E} is always tangential to the lines of forces. But to fully characterize the electric field vector, we need also to give its magnitude. The magnitude, or strength of the electric field, can be measured from the density of lines at a given point. For example, for point charges, the electric field is given by the formula

$$E = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2},\tag{1.2}$$

which predicts that the field intensity increases with decreasing distance, r, from the charge, q. The density of field lines is largest when close to the point charges and quickly decreases with distance. The goal of this experiment is to find the electric field lines for two or three objects.

The electric field lines can be found by plotting the equipotential lines of the electric field. If the large number of points of the same potential needs is found, they may be connected together with a smooth line or surface, which is called an equipotential line or surface. The electric field lines must always be perpendicular to the equipotential lines or surfaces.

1.2 Procedure

The experiment will be performed using the electric field mapping board, high resistance paper, a conductive ink, a power supply (or a battery) and a voltmeter. The conductive ink is produced from copper or nickel flakes in a suspension. When the ink dries, the metal particles settle on the



Figure 1.1: **Experimental setup.** A photograph (left) and schematic (right) of the experimental setup.

top of each other, forming a conductive path. The resistance of the ink is about 2 to 5 Ω /cm and can be neglected in comparison with the resistance of the paper, which is 20,000 Ω /cm. Therefore, the potential drop across the electrodes can be considered negligible.

- 1. Place the conductive paper on a smooth surface (do not place it on the corkboard) and draw the electrodes with the conductive ink. Shake the conductive ink can vigorously for about one minute. Keep the can perpendicular to the paper while drawing the electrodes. When the line you made is spotty, shake the can again and draw over the line. A smooth solid line is essential for good measurements. Let the ink dry for about 20 minutes before making measurements. Therefore, plan your experiments and draw the electrodes as soon as possible.
- 2. Mount the conductive paper on the corkboard using push pins in the corners and connect the electrodes to a power supply (or a lantern battery) and to the voltmeter. Make sure that there is a good contact between the line, a wire, and the pin. If the electrode has been properly drawn, and a good electric contact has been established, the potential drop across the electrode should be less than 1%. If the voltage across the electrode is greater than 1%, then remove the pins from the corkboard and draw over the electrodes a second time with the conductive ink, or find another place to hook up the wire.
- 3. The equipotential surfaces are plotted by connecting one lead of the voltmeter to one of the electrode push-pins. This electrode becomes the reference. The other voltmeter lead (the probe) is used to measure the potential at any point on the paper simply by touching the probe to the paper at that point. Figure 1.1 (right) schematically indicates the method of mapping equipotentials. To map an equipotential, move the probe to the point at which the voltmeter is indicating the desired potential. Mark this point with a white pencil. Move the probe to a new position which maintains the voltmeter at the same reading. Mark this point. Continue in order to find a series of points at the same potential across the paper. Connect the points with a smooth line and write the potential difference. This is the equipotential line.

4. Repeat the measurements for different potentials between the probe and the reference electrode. Find at least 10 equipotential lines for voltages of 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, and 22 V. From the symmetry, you can guess the 1, 3, 5 V surfaces and so you need not measure them. Do not try to mark the electric field lines; it takes too much time. Do it later at home. If the system has an axial symmetry, you may limit your measurement to one side of the symmetry axis. The equipotentials in the other half can be determined by reflecting the found lines about the axis.

1.2.1 Equipotentials between parallel lines

Find the equipotentials outside and inside the parallel lines which symbolizes a parallel plate capacitor. Next, sketch in lines of electric field force. Remember that lines of force are always perpendicular to equipotential surfaces; and, since conductors are equipotential surface, field lines must be perpendicular to the surface of both conductors. Sketch lines of forces first lightly, and when you have them right, draw them darkly. It is useful to choose a different color for the field lines than that used for the equipotential lines. Keep the same distance between the electric field lines close to the silver lines representing the capacitor. Remember that the electric field lines are perpendicular to the equipotential lines and to the metal surfaces.

In the report, answer the following questions:

- 1. What is the electric field inside the capacitor?
- 2. What is the electric field outside the capacitor? Is it constant?
- 3. How do the edges of the plates affect the electric field? (PHYS 20481 and PHYS 20484 only)
- 4. From the measurements, calculate the components of the electric field at the center of the capacitor and at a point at the edge. Since the potential has been measured in large steps of voltage, you can only estimate the components E_x and E_y from

$$(E_x, E_y) = -\left(\frac{\delta V}{\delta x}, \frac{\delta V}{\delta y}\right) = -\left(\frac{\Delta V}{\Delta x}, \frac{\Delta V}{\Delta y}\right).$$
(1.3)

1.2.2 Equipotentials between two parallel lines with a floating circular electrode

Draw a circular electrode between two parallel lines (Fig. 1.2) and map the equipotentials. The circular electrode symbolizes a hollow metal sphere between the capacitor plates. In the report, answer the following questions:

- 1. How does the circular electrode distort the field? Compare the result with those obtained for two parallel lines.
- 2. What is the electric field inside the circular electrode? What is the field on the electrode surface?
- 3. What is the potential of the circular electrode? What is the potential inside the electrode?



Figure 1.2: Capacitor with a hollow metal sphere between the plates.



Figure 1.3: Simulation of an electric field during a thunderstorm.

1.2.3 Clouds and a house during a thunderstorm.

Draw two electrodes, one in the shape of a cloud, another in the shape of a house. Exaggerate the shape of the roof and make it very sharp (Fig. 1.3). During a thunderstorm, the clouds carry large charges which create an intense electric field between the clouds and the ground. Your electrodes simulate this charge separation and the generated electrostatic field. Map the equipotential lines and mark the electric field lines. In your report, discuss the distribution of the electric field lines, especially in the close proximity of the roof. Where will the lightning strike, outside the house or on the tip of the roof?

Lab 2

Electric measurements

2.1 Introduction

To find the resistance, one needs to measure the voltage across the resistor, V, and the current, I, flowing through the resistor. According to the Ohm's law the resistance, R, is given by the ratio:

$$R = \frac{V}{I}.$$
(2.1)

You will use a digital multimeter to find R, V and I. Our laboratory is equipped with first-rate instruments, which display 4 digits, see picture below. On the voltage scale you can measure 0.5×10^{-4} V to 1999 V; on the current scale you can measure 0.5×10^{-7} A to 10 A. Other multimeters used in this lab have different shapes but they all measure R, V, and I (Fig. 2.1).

As you look at the front panel of the multimeter, you notice that there are black and red jacks. Also on your workbench you may find red and black cables. It is a common practice to use a red wire for high voltage or positive signal and a black wire for low voltage or negative signal. We suggest that you should use this system in the laboratory since it is helpful in checking the wiring. (A different system is used in the wiring of buildings. White denotes the neutral wire; black is used to indicate wires under 120 V AC; red is reserved for 240 V. Green is always used for ground wires.)



Figure 2.1: Multimeters Typical analog (left) and digital multimeters (center and right).



Figure 2.2: **The breadboard.** A breadboard (left) and examples of a good circuit (center) and a bad circuit (left).

2.2 Procedure

Set the meter to measure resistance (ohm, Ω) by depressing the HI Ω function switch. Connect a black lead to the common jack of the multimeter and a red lead to the A- Ω jack. Select a 1000 range. Please note that HI Ω range is set to measure kiloohms, k Ω , combining it with the 1000 range this means that the maximum value to be measured is 1,000,000 Ω or 1 M Ω . Keep the leads apart and the display should flash. The flashing indicates that the measured resistance between two leads exceeds the maximum value of 1 M Ω . Next, grasp two exposed leads, holding one in your right hand and the other in the left hand. The meter will show the resistance of your body. Measure the resistance of your skin by touching two points on your skin about 2 inches apart. The resistance of the skin may vary greatly with the amount of moisture on the skin. If your skin is dry you may have to change the range from 1000 k Ω to 10 M Ω . If it is wet to display more significant digits, you may want to change the range to 100 k Ω .

2.2.1 Resistor color code

Determine the resistance of the 5 resistors provided. Each resistor to be measured must be connected between two posts on the "bread board". The breadboard shown in the photo allows you to built electrical circuits. The openings are designed to fit banana plugs and are arranged in the form of squares. There are nine openings per square. They are all connected internally, but separate squares are isolated. To built a circuit you need to plug in one end of the resistor into any opening in one square and another end into another square. An example is shown in Fig. 2.2. Here a resistor is mechanically attached to a banana plug, which is pushed into holes in adjacent squares. The leads are pushed into other holes in the same squares and a multimeter. You can read a measured value on the display. An example of a BAD connection is shown below. In this photo the black lead is attached to a square with no resistor attached and the display is blank. This circuit is open and the multimeter cannot measure anything.

For your convenience we attached the resistors to banana plugs. There are five different banana plugs with different resistors provided for each setup. The resistors are marked with four or five color bands. This is the resistor color code. The first two bands indicate two significant digits, the third indicates the power of ten, and the fourth band indicates the precision of the measurements. The fifth band (if present) indicates reliability. The color code key for resistors is given in Table

$e_{2.1.}$ mesisu	JI COIOI
First three	bands
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9
Tolerance l	oand
Silver	10%
Gold	5%
No band	15%

Table	2.1:	Resistor	color	code

Table 2.2: Resistance measurements

No.	Measured resistance	Color code value	Difference
	(Ω)	(Ω)	(%)
1			
2			
3			
4			
5			

2.1. Always orient the resistors so that the gold or silver band, the so called tolerance or precision band, be on your right side. For example, a resistor with the following colors (from left to right), brown black red - gold tells us the first digit is 1 (brown), the second digit is 0 (black) and the power of ten is 2 (red). That gives us $R = 10 \times 10^2 \Omega = 1000 \Omega$. The gold band tells us that this is accurate to within 5%, so the actual resistance could range from 950 Ω to 1,050 Ω .

Attach the meter leads to the breadboard and record the displayed values. DO NOT ATTACH ANYTHING TO THE 10 A PLUG OF THE MULTIMETER. Change the range so that the display will show all four digits. For resistance values less then 10 Ω depress the LO Ω and 10 Ω switches. Clip the test leads together. You may observe a non-zero reading (a few tenths of an ohm). The reading is due to the resistance of the test leads, fuses, and jacks. You may adjust the ZERO control (available only on analog meters) until the display shows 0.00, or subtract the value from any readings in this range, if such accuracy is required. Report the measured resistance values in Table 2.2 and compare the data with the values expected from the color code. Compare the difference with the estimated value from the fourth band of the color code.



Figure 2.3: **Resistors in series.** The series circuit shown schematically at the top can be can wired in a number of different ways. The above photographs show two possible series combinations.

R_1	R_2	Measured value	Calculated value	Difference
(Ω)	(Ω)	(Ω)	(Ω)	(%)
1				
2				
3				

Table 2.3: Resistors in series measurements

2.2.2 Resistors in series

Select two resistors of similar values. Measure each resistance. Then connect them in series on the bread board as shown in Fig. 2.3. In the left photo the resistors are plugged into adjacent squares, in the photo on the right the resistors are connected to distant squares and a white bridging plug is used to connect them. There are many other possible arrangements of resistors on the breadboard resulting in a series combination. Record the results. Compare the measured and expected values of two resistors connected in series. For the series combination, the theoretical value can be obtained from:

$$R_{\text{series}} = R_1 + R_2. \tag{2.2}$$

Report the experimental and theoretical values in Table 2.3.

2.2.3 Resistors in parallel

Connect the same two resistors in parallel as shown in Fig. 2.4. he photo shows one of many possible arrangements of the resistors on the breadboard that give the parallel combination. You may want to explore and build your own connections. Note, that you may work with a different multimeter!!!



Figure 2.4: **Resistors in parallel.** The photo on the right shows one possible arrangement of resistors in parallel as shown schematically on the right.

R_1	R_2	Measured value	Calculated value	Difference
(Ω)	(Ω)	(Ω)	(Ω)	(%)
1				
2				
3				

Table 2.4: Resistors in parallel measurements

Make your own arrangement of resistors in parallel. Compare the readings of the meter with the theoretical value:

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2}.$$
(2.3)

Compute the percentage difference and report the experimental and theoretical data in Table 2.4.

2.2.4 Ohm's law

Select a resistor of about 100 k Ω using the color code. IMPORTANT: Use the multimeter to read its actual value and record it in Table 2.5. Set up the circuit on the breadboard as shown in Fig. 2.5. The voltmeter is connected in parallel, the ammeter in series. The 5 volts can be obtained from a power supply you will find on the desk. Make sure that the positive terminal is connected to the red jack on the meter. Use one digital multimeter for "A", the ammeter, and another digital mulimeter for "V", the voltmeter, in the circuit.

The same instrument may be used as a voltmeter or an ammeter, and selecting proper functions is very important. Remember that the ammeter must be connected in series and the voltmeter always in parallel. Since you will use a DC current, select DCA and the range of about 100 μ A for current measurements, and DCV and 10 V range for the voltage measurements. Record the



Figure 2.5: **Ohm's law circuit.** Ammeter is always in series, voltmeter is always in parallel. The photo shows the 100 k Ω resistor connected to a power supply (center) and an ammeter (right). The digital voltmeter (left) is connected in parallel to the resistor. Remember to depress the proper function and range switches.

current, I, and potential, V. Compute V = IR to verify your voltage measurements. The two values agree if the voltmeter has an infinite internal resistance.

Replace the digital voltmeter with a standard voltmeter, as shown in the photo. Do not alter the power supply or the ammeter. The input resistance of the standard meter is smaller then that of the digital meter and may affect the measurements. You can read the value of the input resistance on the meters front panel. Adjust the meter scale appropriately and measure I and V. Compute V = IR.

The difference in the readings can be explained as follows. The resistance of the ammeter, R_A , is essentially zero. The resistance of the voltmeter, R_B , acts as a resistor in parallel with $R = 100 \text{ k}\Omega$. This means that the equivalent circuit can be drawn as shown in Fig. 2.6. The goal of this part of the experiment is to find the input resistance of the standard voltmeter.

The equivalent resistance can be found from the input voltage, which in this case is almost 5 V, and the current in the system.

$$R_{\text{equiv}} = \frac{V}{I}.$$
(2.4)

On the other hand the equivalent resistance can be written as (Eq. (2.3))

$$\frac{1}{R_{\text{equiv}}} = \frac{1}{R} + \frac{1}{R_B}.$$
(2.5)

From these equations one can find the resistance of the voltmeter

$$R_B = R_{\text{equiv}} \frac{R}{R - R_{\text{equiv}}}.$$
(2.6)

Report the calculated values of the input resistances for the digital and standard voltmeters. If you get a negative value for R_B it is probably because you did not measure with sufficient precision the value of R, the approximately 100 k Ω resistor. Always remember to turn off the meters after the measurements. The meters use dry batteries with limited lifetimes.



Figure 2.6: Ohm's law circuit. This is the same circuit as in Fig. 2.5

	Potential	Current	R_{100}	$R_{ m equiv}$	R_B
	(V)	(A)	(Ω)	(Ω)	(Ω)
Digital meter					
Standard meter					

	Table 2.5 :	Ohm's law	measurements
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2.3 Report

In your own words explain:

- when it is practical to connect resistances in series and when in parallel.
- when the internal resistance of a meter is important, how it may affect the measurements and when it can be ignored.
- which meter is a better one?

Lab 3

Series and parallel networks

3.1 Introduction

In this experiment you will examine the brightness of light bulbs that are connected to batteries in different configurations. You will also explore how batteries can be connected and what are advantages of these combinations. In the second part of this lab you will replace qualitative observations of bulb brightness with a quantitative analysis of electric current and voltage. There is no quiz before the lab, but you are required to answer questions listed in this manual and bring them with you to the class.

3.2 Background

3.2.1 Circuit diagrams

Circuit diagrams allow us to represent a circuit on paper using symbols for the batteries, resistors, and light bulbs, switches, etc, instead of drawing these elements or taking a picture. Some common symbols are shown in Fig. 3.1. Wires are represented by lines. When the lines are connected at a point this junction is represented by a thick dot. The symbol for a battery is two parallel lines, one of which is shorter and thicker. The shorter and thicker line represents the negative terminal of the battery and the long line represents the positive terminal. Symbols for a switch and a bulb are shown in Fig. 3.1. Since the bulb is a resistor, the alternative symbol for the bulb is a jagged line.

3.2.2 Equipment

The parts used in this lab are showed in the photograph. The bulbs are mounted onto banana plugs and black and red colors indicate different resistance of the filaments. The batteries also have banana plugs attached to them. Holes in the white breadboard accept banana plugs and black lines indicate holes that are interconnected. It means that connecting a wire to any of nine holes in a square gives the same result. The plug-in board and plug-in elements allow for an easy and transparent construction of connections creating perspectives similar to those in circuit diagrams. **The multimeter is set to measure voltage; please do not change its function.**



Figure 3.1: **Circuit diagram symbols.** From left to right are the symbols for a battery, a switch, a bulb, and two symbols for resistors. Connected wires are depicted with a dot at the junction.



Figure 3.2: Equipment used in Lab 2. You will need a breadboard, multimeter, batteries, bulbs and wires.

3.2.3 Kirchhoffs laws

The sum of currents flowing into a junction point is equal the sum of currents flowing out of this point. This is the first Kirchhoffs rule and basically it states that the current cannot be lost in the junction. Since the current is a measure at which charge is moving through a wire, this rule represents the law of conservation of charge. For the five-way junction, shown in below, this law is expressed algebraically as

$$I_1 + I_2 = I_3 + I_4 + I_5 \tag{3.1}$$

Assigning positive signs to currents into the junctions and negative to currents leaving the junction this equation can be expressed as



A battery is a source of current and also produces voltage across all resistors in a closed circuit. Examples are shown in Fig. 3.3. The circuit is complete when the current leaving the battery, specifically the positive terminal of the battery, may move through different resistors and then returns to the negative terminal of the same battery. Note that the light bulb can be treated as a resistor. The Ohms law defines the potential drop, V, across a resistor, R, with a current, I,

$$V = IR. (3.3)$$

The second Kirchhoffs rule deals with potential drops inside a loop and states that the sum of voltages across all the elements in a loop is zero. In other words, the voltage across the battery is equal the sum of the voltages across the resistors.

$$V = V_A + V_B. \tag{3.4}$$

3.2.4 Series and parallel combinations

Resistors and batteries may be connected together in different combinations. Even the most complicated circuits can be decomposed into series and parallel combinations of resistors (or batteries) and small sub-circuits. In this lab we will focus only on simple circuits, with no subsystems or networks.

When resistors are connected in series, they are connected on one side only. The other sides are connected to other elements of the circuit, see Fig. 3.3 (left). When resistors are connected in parallel they have common connections, all the wires, also called leads, on one side of the resistor are attached together. The leads on the other side of the resistors are also connected together



Figure 3.3: **Bulb circuits.** (left) Two bulbs are connected in series. This forms a complete circuit with current leaving the positive terminal of the battery, flowing through the two bulbs and ending at the negative terminal of the battery. (right) Two bulbs are connected in parallel. The voltages across both bulbs are the same and equal the voltage of the battery.

and usually attached to a battery or another element of the circuit. When resistors connected in parallel are attached to a battery the voltage drop across each resistor in the combination is the same, see Fig. 3.3 (right). This conclusion is the consequence of the second Kirchhoffs rule.

For resistors connected in series, the end of first resistor is connected to the second resistor and the same current flows through both resistors. Thus, for resistors connected in series and attached to a battery, the voltages across individual resistors may vary depending on their values of R, see Eq. (3.3).

3.2.5 Meters

Ammeters and voltmeters are used to measure the current and voltages, respectively. They are designed not to affect the circuits and to minimize their effects ammeters are always connected in series and voltmeters in parallel. Not obeying that rule may result in damaging the meters. At the present time most meters available on the market can work as ammeters, voltmeters or ohmmeters. They come in different shapes and sizes. Each time you change the function of the multimeter you must remember to correctly reconnect the meter to the circuit. As you look at the front panel of the multimeter, you notice buttons or knobs with symbols V, I, and R. Depressing the button V (or turning the knob to symbol V) will set the multimeter to work as a voltmeter. You may also need to select the range for the expected voltage. If you expect that the voltage you will measure is about 3 V it would be wrong to set the meter to be adjusted. A zero reading may indicate that there is no potential difference or that the range is too high. Of course, you will repeat the same procedure for current or resistance measurements.

The meters have several jacks, usually one of them is black and the other is red. Also on your workbench you may find red and black cables. It is a common practice to use a red wire for positive signal and a black wire for negative signal. We suggest that you should use this system in the laboratory since it is helpful in checking the wiring.

3.3 Procedure

1. Select three light bulbs mounted onto BLACK dual banana plugs and a triple holder for AA type batteries. Place two batteries into the holder. Connect the batteries and light bulbs as shown below, starting with the circuit on the left. Measure the voltage across the bulb. Repeat for the two other circuits. Compare your observations with the predictions you made prior to the lab. Record the data the table below.



Bulbs in series measurements

	Voltage	Voltage	Voltage	Voltage across
	across bulb A	across bulb B	across bulb C	the battery
A single bulb circuit				
A double bulb circuit				
A triple bulb circuit				

For the last measurement, with the three bulbs in series, compare the sum of potentials $V_A + V_B + V_C$ with the potential across battery. In the report comment about the observed relationship. Although the bulbs appear to be identical, the potential drops across the bulbs are not the same. In the report provide a feasible explanation. Verify your answer to question No. 7.

2. Connect two light bulbs mounted onto BLACK banana plugs (B, C) and one on a RED banana plug (A) and assemble a circuit as shown below. Measure voltages across the battery and each of the light bulbs. Record your data in the table below. Compare the potentials drops in columns 3, 4 and 5.



Bulbs in series and parallel measurements

Voltage	Voltage	Voltage across	Voltage	Voltage across the
across bulb A	across bulb B	bulbs A and B	across bulb C	battery

3. Build the series-parallel combinations shown below and verify your answer to question No. 8.



4. Build a circuit as shown in the photo below. Record the voltage across every light bulb. Unscrew one of the bulbs. Record the voltage across every light bulb. How have the voltages changed? Why?



	Voltage	Voltage	Voltage	Voltage	Voltage	Voltage
	across A	across B	across C	across D	across E	across F
All bulbs in						
One unscrewed						

Bulbs in series and parallel measurements

5. Select two single battery holders. Place 1.5 V batteries in the holders. Connect the batteries in series, i.e., the positive terminal of one battery is connected to a negative terminal of the other. Measure the total voltage of the battery combination and compare with the voltage across the single battery. Record the result in the table below. Connect the batteries in parallel, i.e., the positive terminals are connected together and the negative terminals are connected together. Measure the voltage across the parallel combination. Record the result in the table below. Connect a light bulb to the combination. Is its brightness different from that of a single battery circuit?

Datteries in series and parallel measurements		
Voltage across a single battery		
Voltage across two batteries		
connected in series		
Voltage across two batteries		
connected in parallel		

Batteries in series and parallel measurements

6. Set up circuits as shown below. Measure voltages across all elements. Write algebraic equations relating the voltages V_{bat1} , V_{bat2} , V_{bulbA} , and V_{bulbB} for both circuits.



3.4 Pre-lab exercises

Please answer the following questions and bring the answers with you to the lab. These answers should be turned in to the TA in place of a quiz.

1. Examine the three arrangements below of a battery, a bulb and two metal wires. In which of the circuits below will the bulb emit light?



- 2. Consider the following statement: The current flows from the positive terminal of the battery to the bulb and is used up in the bulb to produce light. Do you agree with this statement? Explain.
- 3. Two identical light bulbs are connected in series to a battery as depicted in Fig. 3.3 (left). Compare the brightness of both bulbs. What can you conclude about the current through each bulb?
- 4. Two *different* bulbs are connected in series as in Fig. 3.3 (left). Is the brightness of the first bulb the same as that of the second bulb? If we reverse the order of the bulbs, will the result be different?
- 5. Consider a circuit with a battery and a single bulb. Add another identical bulb, B, in series, see the schematics below. Predict the brightness of the bulbs relative to the circuit with the single bulb. Will the brightness of bulb A change?



Add another identical bulb, marked C in the figure below. Predict the brightness of bulb A in the circuit with three bulbs compared to a single-bulb circuit.



6. Consider a circuit with a battery and a single bulb. Add another bulb in parallel as shown below. Predict the brightness of bulb A and compare it with the circuit with the single bulb. Will the brightness of bulb A increase, decrease, remain the same?



7. Two identical bulbs are connected in series, as in the figure below. A 3.0 V battery is the source of the current. What is the potential difference between points on both sides of each of the bulbs? What is the potential difference between these two points if one bulb is removed from the circuit?



8. Consider the three circuits below. Is there a significant change in brightness of bulb A when bulbs B and C are connected? Is there a significant change in brightness of bulb A when the second and third branches are connected? What will happen to the brightness of bulb B when bulb A is unscrewed? What will happen to the brightness of bulbs B and F when bulb E is unscrewed?



Lab 4 Superconductor

4.1 Introduction

Superconductivity was discovered by H. Kamerlingh-Onnes in 1911. Simple metals like mercury, lead, bismuth, and others become superconductors only at very low temperatures of liquid helium. Various alloys were also found to be superconductors at somewhat higher temperatures. Unfortunately, none of these alloy superconductors work at temperatures higher then 23 K. Therefore, for many years superconductivity has been merely an esoteric problem and not many scientists were interested in studying it. Then in 1986, researches at the IBM laboratory in Switzerland, discovered that ceramics from a class of materials called perovskites were superconductors at about 35 K. As a result of this breakthrough, scientists began to examine the various perovskite materials very carefully. In February 1987, a ceramic material was found that was a superconductor at 90 K. In this temperature region, it is possible to use liquid nitrogen as a coolant since nitrogen condenses to a liquid at 77 K. This is an inexpensive refrigerating fluid; and it is feasible that in the near future superconductivity will find some practical applications.

It is necessary to use quantum mechanics to explain the mechanism of superconductivity. At the present time there is no complete theory that explains superconductivity in both metals and ceramic materials. However, it may be assumed that in superconductors electricity is conducted by electrons coupled in pairs. These pairs, called Cooper pairs, are formed at temperatures below the critical temperature, T_c , and they can move through the material without loosing energy. That means that at temperatures below T_c the resistance is zero. Narrow wires could carry large currents without loss in the electric energy (the main cost of transmitting electric power at a distance). However, there is a certain maximum current, I_c , that destroys superconductive properties. At currents larger than I_c the materials stop being superconductors. The goal of this experiment is to find the critical temperature by recording the current and the temperature dependence of resistance of a superconductive disk.

The superconductors you will study have the chemical formula $YBa_2Cu_3O_x$, where x is approximately 7 or $Bi_2CaSr_2Cu_2O_9$. Because metals yttrium (Y), barium (Ba) and copper (Cu) are in the ratio 1 to 2 to 3, the former material is called a 1-2-3 superconductor. The production of 1-2-3 superconductors is very simple. Yttrium, barium and copper oxides are mixed in the correct proportion, poured into a die mold, pressurized to form a disk and fired in a furnace to a temperature of about 1700°F. The bismuth based superconductors are called 2-1-2-2 materials and are made in a similar manner. The 1-2-3 and 2-1-2-2 superconductors have different critical temperatures.



Figure 4.1: Schematic of a four point probe.

To measure the resistance of a ceramic material, we use the four point electrical probe. A schematic of a four point probe is shown in Fig. 4.1. This technique eliminates the effects of contact resistance. This is a very important technique, which is used in measuring resistance of biological materials, polymers and other materials. When the resistance is measured by attaching two wires to a sample, the resistance of the contacts is also measured. For metals this contact resistance is usually small and to a first approximation can be neglected. So when you measure the resistance of a 10 k Ω resistor, for example, the contact resistance of less then 1 Ω can be safely ignored. But for a 1-2-3 superconductor, the resistivity is very small and the contact resistance may appear to be larger than the effect you are trying to measure. In the four point probe the current leads are attached to the sample at different places than the wires which read the potential drop. For a sample with electrical resistance a current flowing through the sample will cause a potential drop between any two points inside the sample. This potential difference can be read by a voltmeter, and it is proportional to the product of the current and the resistance of the sample. The resistance is small; and to increase sensitivity of the voltage measurements, the current should be between 0.01 and 0.5 A. The voltmeter should have a large internal resistance to minimize the current flow through the portion of circuit comprising the voltmeter. Because there is no potential drop across the contact resistance associated with the voltage probes, only the resistance of the sample is measured.

The superconductor is placed in a metal holder to protect it from thermal shock and mechanical stresses. Six wires are attached to the cylinder. Four form the four point probe and two are connected to a thermocouple inside the device. Thermocouple wires are connected together and this joint produces a small potential drop. This voltage can be measured by any voltmeter and converted into temperature. You may use a digital voltmeter and the conversion table shown below; or a digital thermometer which will display the temperature of the superconductor in degrees Kelvin. Of course, the conversion table is built into a microprocessor, a part of the thermometer which is nothing more than a voltmeter. You will use T-type or K-type thermocouples which are made of

copper and constantan, or chromel and alumel, respectively. Constantan is a copper-nickel alloy. Chromel is an alloy of Ni and Cr and alumel contains Ni and Al.

4.2 Procedure

Safety instructions

You will do the experiment at very low temperatures. Be very careful when working with liquid nitrogen. Do not touch liquid nitrogen or any object immersed in this fluid. Moisture on your fingers can freeze almost instantaneously when exposed to such low temperatures. As a result your skin may be "glued" to the metal and fingers may also freeze. When pouring liquid nitrogen be careful to prevent any splashing. Do not cover a container with liquid nitrogen in it with a tight-fitting lid. When nitrogen evaporates, the pressure inside the container may increase causing an explosion.

Do not expose the superconductor to water. After the experiment, wait for the cylinder to warm to room temperature and wipe it to remove frost or water. Later use a hair drier to ensure that it is dry. Do not increase temperature above 100°F. Store the superconductor in a box with some drying agent, like silica gel.

- 1. Attach two black wires to a digital voltmeter and the red wires to an ammeter and a power supply. Attach the thermocouple to a voltmeter or a digital thermometer. Set the thermocouple reader to read the T or K thermocouple. You can read the symbol of the thermocouple on the plastic connector attached to the thermocouple. Do not bend the thermocouple. Place the cylinder, with the wires attached, into a thermos with sand and pour liquid nitrogen into it. Read the potential across the thermocouple. When the cylinder is completely cooled and the temperature drops to about 70 K you can turn the power supply on. Adjust the power supply so the ammeter will read 0.1 A. It is a special power supply designed to keep the current steady. When the resistance of the superconductor changes with decreasing/increasing temperature, the voltage output will change appropriately to keep the current constant. Read the potential difference on the voltmeter. Use the 200 mV scale. At 70 K, there should be no potential difference between the voltage probes.
- 2. Let nitrogen evaporate slowly from the thermos. Read the temperature and observe the potential across the superconductor. You should record about 20 voltages in the temperature range between 80 and 120 K and an additional 20 points between 120 and 200 K. From time to time check the ammeter readings. If necessary, adjust the current to keep it constant.
- 3. The ratio of the voltage to the current flowing through the sample is the resistance of the superconductor between the two voltage probes. Since you kept the current constant, to get the resistance you will divide the voltages by the same number. If this resistance is plotted versus the thermocouple reading, the result should be similar to that shown in Fig. 4.2. Present your resistance measurements in the form of a graph and determine the critical temperature, at which the resistance gradually decreases to zero. Assess the error. Note, that the 1-2-3 and 2-1-2-2 superconductors have different critical temperatures, 92 K and 110 K, respectively. Identify your superconductor.



Figure 4.2: Temperature dependence of resistance of a superconductor.

4.3 Report

In your report answer the following questions:

- 1. Why did the liquid nitrogen boil when you poured it into the thermos?
- 2. When the nitrogen evaporates the cylinder becomes covered with a layer of white frost. This is a mixture of dry ice (solid CO_2) and regular ice (H₂O). Explain why CO_2 and H₂O condense on the cylinder.
- 3. A two probe method of measuring the resistance of the superconductor below the critical temperature shows a non-zero value. Why?
- 4. Explain the difference between a superconductor, a semiconductor, and a resistor.

Lab 5

Temperature Coefficient of Resistivity

5.1 Introduction

Resistance of any material varies with temperature. For temperature range that is not too great, this variation can be represented approximately as a linear relation

$$R_T = R_0 [1 + \alpha (T - T_0)], \tag{5.1}$$

where R_T and R_0 are the values of the resistance at temperature T and T_0 , respectively. T_0 is often taken to be 0 °C. α is the temperature coefficient of resistivity. Pure metals have a small, positive value of which means that their resistance increases with increasing temperature. From temperature measurements of R you can find α . To do this you will plot resistance values versus T, and approximate the results with a straight line. The intercept of this line with the resistance axis is R_0 , and the slope divided by R is the value of α .

There are materials in which resistance decreases with increasing temperature. A thermistor is an example of such a material. It is made of semiconductors, such as oxides of manganese, nickel and cobalt mixed in the desired proportion with a binder and pressed into shape. Thermistors are very sensitive to even small changes of temperature, therefore they are often used as thermometers. The change of resistance of a thermistor caused by temperature change is a nonlinear function and can be approximated by the following formula

$$R_T = R_0 \exp\left[\beta \left(\frac{1}{T} - \frac{1}{T_0}\right)\right],\tag{5.2}$$

where R_T and R_0 are the resistance values at absolute temperatures T and T_0 (on the Kelvin scale), β is a constant over a limited temperature range and characterizes a property of material. The unit of β is degree Kelvin. Equation (5.2) can be expressed as

$$\ln\left(\frac{R_T}{R_0}\right) = \frac{1}{T} - \frac{1}{T_0}.$$
(5.3)

When the resistance is measured at various temperatures and $\ln(R_T/R_0)$ is plotted against $(1/T1/T_0)$, a straight line is formed. β can be found from the slope of that line.

Some materials have very complicated temperature dependencies of resistance. For example, nichrome wire, used as a heating element in most space heaters, practically does not change its



Figure 5.1: **Temperature dependence of resistance.** Variation of resistance with temperature of a metal (left) and a semiconductor (right).



Figure 5.2: **Temperature dependence of resistance.** Temperature dependence of resistance for an alloy (left) and a carbon resistor (right).

resistance in the temperature range between 0 °C and 100 °C. Fig. 5.2 (left) illustrates this dependence, and it could be approximated by Eq. (5.1). For other materials, such as carbon resistors, R may be constant for a narrow temperature range and show a large effect beyond that range. Fig. 5.2 (right) shows an exaggerated temperature dependence for this type of material.

5.2 Procedure

- 1. Open the plastic box with resistors and fill it with water. The resistors should be completely immersed in water. Close the box and secure the cover with electrical connections inside. Insert a thermometer, it should be immersed in water to the level indicated by a horizontal line. Connect the binding post of the terminal to an ohmmeter. Stir the water thoroughly and record the initial values of temperature and resistors in the box. Use the rotary switch to measure resistance of each of the resistors.
- 2. Turn the heater on by closing the switch on the top plate of the box. Increase the temperature by about 5 degrees. Keep stirring the water. Turn the heater off and continue stirring until water reaches thermal equilibrium. Record the resistance of each resistor in the box and the temperature. Repeat this procedure in approximately 5 °C intervals until you have at least 10 readings or the temperature reaches 90 °C. Do not increase the temperature above 90 °C. Record the data in the table below. To reduce the error use the same setting of the ohmmeter for the same resistors. Because the materials whose resistance you will measure have different values of R you will have to set the ohmmeter to ranges appropriate for each element. Remember to use the same ranges for each of the resistors.

Tresistance versus temperature measurements.					
Temperature	Resistance	Resistance	Resistance	Resistance	Resistance
	conductor 1	conductor 2	conductor 3	conductor 4	conductor 5
(°C)	(Ω)	(Ω)	(Ω)	(Ω)	(Ω)

Resistance versus temperature measurements.

Conductor	$\alpha ~(/^{\circ}C)$
Copper	4.29×10^{-3}
Iron	6.41×10^{-3}
Nickel	6.00×10^{-3}
Platinum	3.93×10^{-3}
Mercury	0.89×10^{-3}
Chromel	0.58×10^{-3}
Nichrome	0.40×10^{-3}

Table 5.1: Temperature coefficient of resistivity for selected materials.

5.3 Report

- 1. Examine your data and identify the metals, the thermistor, the carbon resistor, and the alloy.
- 2. For the two metal resistors and the alloy use Eq. (5.1) to determine the thermal coefficient of resistance, α . Plot normalized resistance, R_T/R_0 , versus T and from the slope of the straight line drawn through the experimental points find α . I recommend that you use Excel or another software and a fitting routine to determine the slope. R_0 is the value of the resistance at room temperature. Identify the metals by comparing the obtained results with the values in Table 5.1.
- 3. For the thermistor plot a graph of $\ln(R_T/R_0)$ versus $1/T 1/T_0$ and find the slope of the straight line, which is the value of β in Eq. 5.2.
- 4. For the carbon resistor plot R vs. T and determine the maximum temperature for which the resistance is approximately the same as at room temperature.
- 5. In the discussion section explain how you identified the materials and estimated the experimental errors. Estimate the precision of the constants α and β .
- 6. In the introduction use a collision model between electrons and nuclei to explain why resistance of pure metals increases with increasing temperature.
Lab 6

Transformer

6.1 Introduction

In this experiment you will study electrical characteristics of transformers. In early nineteenth century Oersted discovered that magnetic field always surrounds a current-carrying conductor. Later M. Faraday demonstrated that a change in magnetic flux, Φ , generates an electromotive force, ε :

$$\varepsilon = -\frac{\mathrm{d}\Phi}{\mathrm{d}t}.\tag{6.1}$$

The negative sign is in recognition of Lenzs law.

An iron-core transformer, Fig. 6.1, is an important device used in alternating current (AC) circuits, which involve these two discoveries. A transformer allows efficiently increase or decrease the line voltage. In its simplest form, the AC transformer consists of two coils of wire wound up around a core of iron as illustrated in Fig. 6.1.

The core directs the magnetic flux produced by alternating current in the first coil, called the primary, the other coil, called the secondary coil. The core has also another function. It can increase the magnitude of the magnetic flux. The changing flux through the secondary coil induces an alternating electromotive force of the same frequency on its terminals. Thus, electrical power may be transmitted. The efficiency of commercial transformers is usually better than 90%. For the sake of simplicity, we will first focus on an ideal transformer, which, by definition, has an efficiency of 100%. Later, we will consider energy losses in actual transformers.

6.1.1 Ideal transformers

When the magnetic flux through a coil of N turns changes at the rate $d\Phi/dt$, the induced electromotive force ε is given by

$$\varepsilon = -N \frac{\mathrm{d}\Phi}{\mathrm{d}t}.\tag{6.2}$$

Thus, the voltage across the primary is expressed by

$$\varepsilon_p = -N_p \frac{\mathrm{d}\Phi}{\mathrm{d}t}.\tag{6.3}$$



Figure 6.1: Schematics of an ideal transformer. N_p and N_s are numbers of turns in the primary and secondary coils, respectively.

Since it is an ideal transformer, all magnetic filed lines are remain within the iron core and the induced electromotive force in the secondary coil can be expressed as

$$\varepsilon_s = -N_s \frac{\mathrm{d}\Phi}{\mathrm{d}t}.\tag{6.4}$$

Often, instead of the electromotive force, we use the effective voltage V which is related to the electromotive force

$$V = \sqrt{2}\varepsilon \tag{6.5}$$

Solving Eq. (6.3) for $d\Phi/dt$ and substituting the result in Eq. (6.4), gives

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}.$$
(6.6)

When the primary coil has fewer turns than the secondary, the voltage across the terminals of the secondary coil will be greater than the primary voltage by the ratio N_s/N_p . Such a transformer is called a step-up transformer. When the number of turns in the secondary coil is less than in the primary, the secondary voltage is reduced and such a transformer is called a step-down transformer.

The ideal transformer has zero power loss, that is, the power input in the primary, $V_p I_p \cos \theta_p$, (θ is the phase angle between V and I) must be equal the power output in the secondary, $V_s I_s \cos \theta_s$. Since $\theta_p = \theta_s$, for the ideal transformer

$$V_p I_p = V_s I_s. ag{6.7}$$

Combining Eq. (6.6) and Eq. (6.7) we find

$$I_p = I_s \frac{N_s}{N_p}.$$
(6.8)

This equation states that the current ratio is inversely proportional to the turn ratio of the coils. In welding operations, when heat is generated by high currents and for the safety reasons, the associated voltage is small, the step-down transformers are used. The step-up transformers are used at the generators to produce high voltages for efficient transmission of power. Step-down transformers are used at the other end of the transmission line to reduce the voltage to the convenient level.

6.1.2 Energy losses in transformers

Efficiency of a transformer is defined as a ratio of the output power to the input power. In commercial transformers the efficiency is usually better than 90%. The power losses in transformers are primarily due to loss of the flux, eddy currents, magnetization and demagnetization of the core, and resistance heating in the coils, and the change in the phase angle, θ_s .

To reduce the eddy currents the core is built from laminated and insulated sheets of the metal. The resistance of thin sheets of metal is increased and resistance of the core prevents the buildup of large eddy currents. To reduce heat losses in the coils they are built from metals of small resistance. Magnetization and demagnetization of the core requires energy. It is often called the hysteresis loss. To minimize this loss special metal alloys are used, usually silicon steel. Flux leakage is typically caused by breaks between elements of the core. To minimize these losses the cores are made from a single piece of a metal. In the experiment, the core is made of two parts, the U-shape core and the yoke.

6.2 Procedure

Assemble a transformer using two coils, one with 1000 turns and the other with 500 turns. Place the iron core in the shape of letter U into both coils and attach the iron yoke, with the bare side inward, to both ends of the U-core. Mount the transformer onto the breadboard and connect the primary coil to the power supply.

6.2.1 Transformer characteristics with no load on the secondary

1. Connect the terminals of the secondary coil to a voltmeter. Make sure that the AC voltage and the range up to 20 volts are selected. Connect another voltmeter to the terminals of the primary of the transformer. Increase the voltage of the power source and record both the primary and the secondary voltages in the table below.

V_p (V)	V_s (V)	V_s/V_p

Transformer measurements — no load on secondary.

2. Repeat the measurements with the coils exchanged and record the results below. In your report compare quotients V_s/V_p and N_s/N_p .

		U
V_p	V_s	V_s/V_p
(V)	(V)	

Transformer measurements — no load on secondary with coils exchanged.

3. Turn the power off and remove the yoke from the transformer, but leave the U-core inside. Repeat the last measurement for one arrangement of coils. Record the results in the table below.

Iransformer with no yoke.				
V_s	V_s/V_p			
(V)				
	(V)			

• . 1 1

6.2.2Transformer characteristics with a load on the secondary

1. Using the 500 turn coil as a secondary connect the circuit as diagrammed in Fig. 6.2 (top). Use 1.0 Ω resistor. Remember to connect the ammeters in series and voltmeters in parallel as shown in Fig. 6.2 (bottom). The digital ammeters must be connected to ports COM and 20 A and the knob must be set to measure AC current. Select the 20 A range. These are sensitive instruments, please be careful how you connect them. Ask the lab instructor to check your setup. Increase the voltage output of the power supply and record primary and secondary voltages and currents. Record data in the table below. Calculate the input power and the output power of the transformer and then its efficiency P_p/P_s .

Transformer with a load on the secondary.

V_p	I_p	V_s	I_s	V_s/V_p	I_s/I_p
(V)	(A)	(V)	(A)		

- 2. (20484 only) Remove the 1.0 Ω resistor and leave the secondary open. It will correspond to an infinite resistance in the secondary. The input power corresponds to the power lost in the transformer due to hysteresis. Please read more about magnetic hysteresis in your textbook.
- 3. (20484 only) Set the input potential to about 20 V. Record the current in the primary. Next, short-circuit the secondary coil. The current is now limited by the impedance of the coil. To operate at the same input current as in the open-circuit test you will need to reduce the input voltage. The low voltage and the low current in the primary generate very low magnetic field and losses due to hysteresis can be ignored. The power that you find for the short-circuited transformer represents the Joule power lost due to resistance in the winding.

6.3 Report

In the report include the following:

- 1. Explain the nature of eddy currents.
- 2. Compare quotients V_s/V_p and N_s/N_p . Are these ratios similar?
- 3. Compare the values I_s/I_p with the ratio of the turns, N_s/N_p . Are these quotients similar?
- 4. Why is the efficiency of the transformer so low? The commercial transformers have efficiency better than 90%. Suggest how to improve the efficiency in the experiment.



Figure 6.2: **Experimental setup for lab 10.** The schematics (top) and a photograph (bottom) of the experimental setup to measure input and output power. The voltmeter to measure potential across the resistor is optional.

Lab 7

AC Circuits and Electrical Resonance

7.1 Introduction

Consider an AC circuit containing a resistor, an inductor, and a capacitor connected in series, as seen in Fig. 7.1 (left). Remember that the same current flows through all three elements. Since the current is common to all elements, we will take it as a reference, and will measure voltages across the resistor, the capacitor and the inductor with respect to the current. It is convenient to present the results in the form of a graph in which the horizontal axis represents the current, see Fig. 7.1 (right). The voltage across the resistor is given by Ohm's law

$$V_R = IR \tag{7.1}$$

and is in phase with the current. Thus, V_R is displayed on the x-axis. The voltage across the inductor,

$$V_L = \omega L I \tag{7.2}$$

leads the current by 90° , and it will be presented along the positive y-axis. The voltage across the capacitor,

$$V_C = \frac{I}{\omega C} \tag{7.3}$$

lags the current by 90° , and is also presented on the vertical axis.

To obtain the resultant voltage, ε , we need to add voltages V_R , V_L , and V_C as vectors. The vector addition is illustrated in Fig. 7.1 (right). Because the vectors V_R and V_C or V_L form a right triangle, ε may be found from

$$\varepsilon^2 = V_R^2 + (V_L - V_C)^2.$$
 (7.4)

Substituting Eqs. (7.1)–(7.3) into Eq. (7.4), leads to

$$\varepsilon = I\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} = IZ,\tag{7.5}$$

where $Z = \sqrt{R^2 + (\omega L - 1/\omega C)^2}$, and is called the impedance of the circuit. The phase difference between the current, I, and the line voltage, ε , is given by

$$\tan \phi = \frac{\omega L - \frac{1}{\omega C}}{R}.$$
(7.6)



Figure 7.1: **AC circuits.** For an AC circuit containing a resistor, an inductor and a capacitor in series (left), the voltages across the three components are represented in a phase diagram (right).

From Eq. (7.6) it is seen that for $\omega L = 1/\omega C$ the phase difference, ϕ , is zero and the impedance, Z, equals R. This condition

$$\omega L = \frac{1}{\omega C} \tag{7.7}$$

is called resonance, and it can be reached by changing any of the quantities ω , C, or L. In this experiment, to reach resonance, you will change only C, while ω and L remain fixed. When the Z equals R, the current is maximum and the circuit is said to be in resonance.

In this experiment you will find the resonance by changing the capacitance of the system. The frequency ω is determined by the power supply, in this case it is 120π /s. ω measured in radians per second, and is related to the frequency f = 60 Hz, measured in cycles per second as $\omega = 2\pi f$. To find the resonance (remember the condition $\omega L = 1/\omega C$) you also need to know the values of L and C. Therefore, the experiment is divided into two parts, first, you will find inductance L, and second you will determine the value of C that leads to the resonance.

7.2 Procedure

The RLC circuit was built and installed inside a box with a transparent plastic cover so you can see all the connections inside, (Fig. 7.2). In addition there are several binding posts, which enable voltage measurements between different elements. Do not touch metal parts of the posts with your hands. To measure the voltage use special leads provided.

7.2.1 Finding the inductance

- 1. DISCONNECT THE POWER CORD.
- 2. Insert the plug into J2 and connect the leads to binding posts P4 and P5 on the box.
- 3. Set all capacitor switches to the open position.
- 4. Set the selector switch to the P (primary) position.



Figure 7.2: RLC circuit. Experimental setup of the RLC circuit with an ammeter attached.

- 5. Plug in the power cord and measure the voltage (remember to set the voltmeter to ACV) between P1 and P4. If this voltage is about 115 V, proceed to step 6. If it is not, disconnect power cord and reverse the connection to P4 and P5. Plug in power cord and measure the voltage between P1 and P4. If this voltage is not 115 V±10 V, ask for assistance before proceeding to step 6.
- 6. Measure the following voltages:
 - V_L , voltage across the inductor, between posts P1 and P5.
 - V_R , voltage across the resistor, between P4 and P5.
 - ε , line or input voltage, between P1 and P4.
- 7. Record the value of the resistor R, this value is marked on the plastic cover.
- 8. The actual phase diagram for the experimental circuit may differ from the theoretical diagram shown in Fig. 7.1 (right). This discrepancy is caused by the resistance of the wire, which was used to make an inductor. An inductor is a solenoid with many windings and the total length of the wire may be hundreds of meters. Also the wire used is typically very thin, which may result in a significant ohmic resistance of the inductor. Therefore, we need to find the resistance of the inductor, we will use symbol R_L to denote this value. Construct a vector diagram of the voltages as follows. Take the voltage V_R as a reference. Remember that this voltage is in phase with the current and draw vector, V_R , on a horizontal line as shown in Fig. 7.3.

Use a suitable scale. Using A as a center, draw an arc of length V_L , and with the origin as a center, draw an arc of length ε . The intersection P, of these two arcs determines the vector diagram of the circuit. Drop a perpendicular from P onto the horizontal axis. The interval PB, which is perpendicular to the horizontal axis, represents the voltage due to the pure inductance. Remember that the voltage due to inductance is perpendicular to the voltage across the resistor. The interval OB represents the voltage due to the total resistance of the circuit, the resistors R and R_L . Since OA is the voltage across the resistor R, the interval



Figure 7.3: **Real phase diagram.** The actual phase diagram differs from the ideal case because of the resistance of the inductor.

AB represents the voltage due to the resistance of the inductor, R_L .

$$(AB) = IR_L. (7.8)$$

Since $I = V_R/R$,

$$R_L = R(AB)/V_R. \tag{7.9}$$

The interval PB represents the voltage due to the inductance, L, of the inductor

$$(PB) = I\omega L \tag{7.10}$$

and

$$\omega L = R(PB)/V_R. \tag{7.11}$$

9. DISCONNECT THE POWER CORD. Remove the plug from J2 and set the selector switch to the S position. With the digital meter set to ohms, measure the resistance of the inductor, P1 and P3. You measured directly the ohmic resistance of the inductor, R_L . In the report, in the discussion section, explain why a value lower than that obtained above is obtained in this direct current measurement.

7.2.2 Finding the resonance

- 1. DISCONNECT TBE POWER CORD.
- 2. Set the selector switch to the S position.
- 3. Insert the plug in J2 and connect the leads to the ammeter, as in Fig. 7.2. Set switch on the ammeter to the 50 mA position.
- 4. Plug in the power cord. Measure and record the current on the ammeter, the line voltage, ε , between posts P2 and P3, the voltage across the capacitors, V_C , across P1 and P2, and the voltage across the inductance, V_L , between P1 and P3, for various values of capacitance. By closing the switches you can get different values of resultant capacitance. The capacitors are connected in parallel and to find the resultant capacitance just add the values of individual

capacitances printed on the box. Start from zero and increase C in steps of $0.1 \,\mu\text{F}$. You will observe that with increasing C the current increases, reaches the maximum, and then decreases. Near the maximum change the step to $0.05 \,\mu\text{F}$ and even to $0.02 \,\mu\text{F}$. These additional points will enable better characteristics of the maximum, and thus the resonance conditions.

5. Graph the current, I, the line voltage, ε , the voltage across the capacitor, V_C , and the voltage across the inductor V_L as a function of capacitance, C, (on the horizontal axis). You will need 10 to 20 points to make good quality graphs.

7.3 Report

In this experiment graphs are very important, and all conclusions should be based on the analysis of the graphs. Two quantitative checks of the theory are possible. The maximum current occurs when $\omega L = 1/\omega C$, or when

$$C = \frac{1}{\omega^2 L}.\tag{7.12}$$

We will call this value the resonance capacitance and denote it as C_{res} . Remember that $\omega = 2\pi f$. Using f = 60 Hz, the frequency of the current and the value of the inductance, L, determined in section 2.1, calculate C_{res} and compare to the experimental value obtained from the graph. According to Eq. (7.5) the maximum value of the current is when Z = R.

$$I_{\max} = \frac{\varepsilon}{RT} \tag{7.13}$$

where R_T is the total resistance of the circuit. Taking into account the small resistance of the ammeter, R_T is given by

$$R_T = R_L + R_M \tag{7.14}$$

where R_M is the resistance of the meter (measured with an ohmmeter) and R_L the resistance of the inductor obtained in section 2.1 (also measured with the ohmmeter). Calculate the maximum value of the current and compare with the value obtained in the experiment. In the introduction discuss applications of the series combinations of R, L and C. Also, explain what the electrical resonance is.

Lab 8

Measurement of the Mass of an Electron

8.1 Introduction

An electron travelling with a speed, v, perpendicular to a uniform magnetic field, B, will experience a force, F, with a magnitude,

$$F = evB, \tag{8.1}$$

where e is the charge of the electron. The direction of the force is perpendicular to the plane defined by the direction of v and B. The force is always perpendicular to the direction of motion of the electron. The electron moves in a circular path of radius r, with the magnetic force supplying the centripetal force. That is

$$F = evB = F_c = m\frac{v^2}{r},\tag{8.2}$$

where m is the mass of the electron. Solving for v, we have

$$v = \frac{eBr}{m}.$$
(8.3)

The electron speed v is acquired by accelerating the electron through a potential difference,

$$eV = \frac{1}{2}mv^2. \tag{8.4}$$

Substituting for v we find

$$eV = \frac{1}{2}m\left(\frac{e^2B^2r^2}{m^2}\right) \tag{8.5}$$

which reduces to

$$\frac{e}{m} = \frac{2V}{B^2 r^2}.\tag{8.6}$$

Hence, by knowing or measuring e, V, B, and r, the mass of the electron can be computed.



Figure 8.1: **Experimental setup.** Schematic of the connections between the power supply, heater and coils.

8.2 Procedure

The apparatus used in this experiment consists of a cathode tube, Helmholtz coils, two power supplies and an ammeter. The cathode ray tube is filled with hydrogen gas at low pressure of about 0.01 mm Hg. In some tubes, hydrogen gas is replaced by mercury vapor. Electrons collide with hydrogen, ionize them, and when atoms recombine with stray electrons, the characteristic green light is emitted. The emission occurs only at the points where ionization took place; therefore, a beam of electrons is visible as a luminous streak in a dark room.

The tube used in the experiment has been designed in such a way that the radius of the circular path of the electron beam can be conveniently measured. The electrons are emitted by the indirectly heated cathode, and are accelerated by the applied potential V between the filament and the anode. The cathode and the anode are constructed in such a way that only a narrow beam is allowed to pass the anode. Outside the anode, the electron beam moves with constant speed. When the beam is inside a magnetic field, it will move along the circle with a diameter given by Eq. (8.2).

A pair of Helmholtz coils produce an almost uniform magnetic field near the center of the coils which can be given by

$$B = \frac{8\mu_0 NI}{\sqrt{125}a},$$
(8.7)

where B is the magnetic field in teslas, N is the number of turns of wire in each coil, I is the current through the coils in amperes, and a is the mean radius of each coil in meters, which is equal to the distance between the coils. In the Helmholtz coils used in the experiment the number of turns is 130 and the radius is 15 cm.

- Connect the heater and the anode of the vacuum tube to the high voltage power supply. The heater should be connected to a 6 V terminal. The anode voltage should be between 150 and 300 V. The coils have their own power supply with the voltage set to 12 V. Check the wiring (Fig. 8.1) and if you have any questions, ask the assistant for help.
- 2. Turn on the power. As soon as the cathode starts to glow, increase the anode voltage so that the beam will be as sharp as possible. Do not increase the potential above 300 V.

3. Turn on the power supply of the Helmholtz coils. Select a value of the current in the coils; it should be between 0.5 and 2 A. Compute the magnetic field. Measure the diameter of the circular beam and record the current in the coils and the accelerating potential between the anode and the cathode. Increase the accelerating potential and record the beam radius. Repeat this procedure for 4 different accelerating potentials. To reduce the experimental error, read the beam diameter several times. Record your results in the following table.

Coil current	В	Anode voltage	Radius of circle	e/m	m
(A)	(T)	(V)	(m)	(C/kg)	(kg)

Experiment 9 measurements.

- 4. Repeat the above procedure with a different value of the coil current. You should have at least 10 different readings for different combinations of experimental parameters. From Eq. (8.6) find the e/m ratio and then calculate the mass of the electron, assuming that its charge is known and equals $e = 1.602 \times 10^{-19}$ C.
- 5. Since you have at least 10 experimental data points for m you can determine the mean value, < m >, and the standard deviation, Δm . The mean value and standard deviation are defined as

$$\langle m \rangle = \frac{\sum_{n} m_{n}}{N}$$
 (8.8)

$$\Delta m = \sqrt{\frac{\sum_{n} (m_n - \langle m \rangle)^2}{N - 1}},$$
(8.9)

where m_n are the measured values, n is the running number which varies from 1 to N, and N is the total number of points. Within the error, the mean value should be equal the expected textbook value, if not, discuss any discrepancy.

8.3 Report

Calculate the mean value of mass and estimate the error. In the report, discuss the following topics:

- 1. The e/m ratio can also be found from the method used by Thompson. Explain the principle difference between each method.
- 2. Discuss the effect of the earth's magnetic field on the result of this experiment. Could you correct this effect? How?
- 3. Compute the velocities of electrons for all accelerating voltages used.
- 4. (For 20481 and 20484) Use the Biot-Savart law to derive Eq. (8.7) for the magnetic field. Find the change in B as you move a distance r from the center between the coils.

Lab 9

Magnetic Force on a Current-Carrying Conductor

9.1 Introduction

Solenoid is constructed by winding wire in a helical coil around a cylinder. The windings are very close to each other and usually consist of many layers. When a current is carried by the wire, a magnetic field of unique properties is generated by the solenoid. If the length of a solenoid is large compared with its diameter, the magnetic field created inside the solenoid is very uniform and parallel to the axis. The magnetic field outside the solenoid is very small and decays quickly with the distance. The magnitude of the magnetic field in the center of the solenoid is proportional to the number of turns per unit length of the solenoid, n, and to the magnitude of the current, I

$$B = \mu_0 n I, \tag{9.1}$$

where $\mu_0 = 4\pi \times 10^{-7}$ Wb/Am. For solenoids that are not very long, we use a more accurate formulae for the magnetic field,

$$B = \mu_0 n I \frac{L/2}{[(L/2)^2 + R^2]^{1/2}},$$
(9.2)

where L is the length and R is the radius of the solenoid.

When a wire carrying a current is placed in an uniform magnetic field a force is exerted on the wire. This force depends on the magnitude of the current, I, the length of the wire, d, and on the relative orientation of the wire with regard to the magnetic field, B, and can be written as

$$\vec{F} = I\vec{d} \times \vec{B},\tag{9.3}$$

where \times denotes the cross product of vectors \vec{d} and \vec{B} . When the wire is perpendicular to the magnetic field Eq. (9.3) simplifies to

$$F = IdB. (9.4)$$

The direction of the force F is given by the right hand rule. Thus, if the force F is known the magnetic field can be found from

$$B = \frac{F}{Id}.$$
(9.5)



Figure 9.1: **Experimental setup.** A schematic (left) and a photograph (right) of the experimental setup. You may use different equipment or use terminals A and B to get power, but the schematics will remain unchanged.

9.2 Procedure

- 1. The air core solenoid is made of enameled copper wire wound on a phenolic core. The ends of the wire are brought out to the brass binding posts on the rigid end plates. The solenoid is about 15 cm long and its interior diameter is about 5 cm. There are five layers of turns. Measure and record the length of the loop current perpendicular to the field, the length, L, and radius, R, of the solenoid as well as the number of turns per unit length.
- 2. Place the loop with pivot wires inside the solenoid and make sure that it can freely oscillate on support brackets attached to the end plate of the solenoid. If necessary adjust the balance by stretching or bending the hook attached to the plastic beam. Make sure that the loop is in the horizontal position before turning the current on. Use a T-shaped aluminum block to make sure that the beam is in the horizontal position.
- 3. Connect the solenoid to the ammeter, A_S , and the DC terminal of the power supply, as shown in Fig. 9.1. Some power supplies are equipped with ammeters and then you do not need additional meter. Alternatively, connect the solenoid to an ammeter, a variac and to the terminal A on your workbench.
- 4. Connect the loop to the ammeter, A_L , and to the power supply as shown in Fig. 9.1. Use only the DC output. Alternatively, connect the solenoid to an ammeter, a variac and to the terminal B on your workbench. If both ammeters do not indicate any current make sure that the power is on and ask the TA check your circuit.
- 5. You may adjust the current by rotating the voltage knob on the front panel of the power supply (or a brush of the variac). **Do not increase the current above** 5 A. Set both the solenoid and the loop currents to zero to see that the plastic beam is balanced. Increase both currents to about 2 A and the end of the beam close to you should move upward. If it



Figure 9.2: **Beam in a solenoid.** The beam is the horizontal position because the two forces, magnetic and due to gravity are equal but pointed in opposite directions. The broken arrow shows the direction of the magnetic field generated by current flowing through the solenoid.

moved downward you will have to reverse the direction of the current in either the solenoid or the loop by switching the wires. When the loop current is turned on the balance is changed because the force F given by Eq. (9.4) is exerted on the loop, see Fig. 9.2. Note that only the part of the loop, which is perpendicular to the magnetic field produces this force. The currents flowing through the two conductive strips parallel to the symmetry axis of the solenoid do not interact with the magnetic field and can be ignored. The plastic beam has the length adjusted in such a way that the end of the beam with the conductive strip is right in the center of the solenoid, where the magnetic field can be precisely determined from Eq. (9.5).

6. With the solenoid current set to 2 A adjust the loop current to achieve balance for each of the weights provided. The weights are in the form of short wires that can be hang on the hook at the end of the beam. Repeat the measurements for the solenoid currents of 3, 4 and 5 A. If you cannot increase the current to the desired value, you may have to adjust the current limit by rotating the current knob on the front panel of the power supply. Write your data in the table below.

Number	F = mg	I_L	I_S	Magnetic field
of wires				$B = F/I_L d$
	(N)	(A)	(A)	(N/Am)
1			2	
1			3	
1			4	
1			5	
2			2	
2			3	
2			4	
2			5	
3			2	
3			3	
3			4	
3			5	

7. The goal of this experiment is to find the magnetic field. Compute the magnetic field for each set of data in Table 1. Find the average values of B (as the ordinate) for the different loop

currents, I_L , and plot these values versus the solenoid current (as the abscissa). Calculate the deviations of the mean values and mark them as vertical bars on your graph. Plot a straight line through the points on the graph in such a way that it will pass through the error bars. Compare the slope of the graph with the value obtained from Eq. (9.2). The slope should be given by $\mu_0 n(L/2)/[(L/2)^2 + R^2]^{1/2}$. Compare both results and discuss discrepancies.

9.3 Report

Course 20481: In the introduction start with the Biot-Savart law and derive Eqs. (9.1) and (9.2). Course 10161: In your report answer the following questions:

- 1. When the loop is placed inside the solenoid and direction of the current is reversed, the plastic beam will move in the opposite direction. Explain.
- 2. Two parallel conductors with currents flowing in the same direction attract each other. In the solenoid the wire windings may be treated as parallel loops, and the coil should be compressed. Is this effect important and if yes, estimate it for your experimental setup.
- 3. Could you use a permanent magnet to do this experiment? Explain.

Lab 10

Microwave Optics

10.1 Introduction

Optical phenomena may be studied at microwave frequencies. Using a three centimeter microwave wavelength transforms the scale of the experiment. Microns become centimeters and variables that are obscured by the small scale of traditional optics experiments are easily seen and manipulated. The microwave system is composed of a microwave transmitter, a detector, a goniometer, a rotating table and other accessories.

The Gunn diode transmitter provides 15 mW of coherent, linearly polarized microwave output at a wavelength of 2.9 cm. The unit consists of a Gunn diode in a 10.5 GHz resonant cavity, a microwave horn to direct the output and an 18 cm stand to reduce table reflections. The output is linearly polarized along the axis of the diode and the attached horn radiates a strong beam of microwave radiation centered along the axis of the horn.

Caution: The output power is well within standard safety levels. Nevertheless, one should never look directly into the microwave horn at close range when the transmitter is on. Under some circumstances, microwaves can interfere with electronic medical devices. If you use a pacemaker, or other electronic medical devices, check with your doctor to be certain that low power microwave at a frequency of 10.5 GHz will not interfere with its operation.

The microwave receiver provides a meter reading that is proportional to the intensity of the incident signal. A microwave horn, identical to that of the transmitter, collects the microwave signal and channels it to a diode in a 10.5 GHz resonant cavity. The diode responds only to a component of a microwave signal that is polarized along the diode axis. Therefore, before taking the measurements adjust the polarization angles of both the transmitter and the receiver to the same orientation. The intensity selection settings (30X, 10X, 3X and 1X) are the values by which you must multiple the meter reading to normalize your measurements. That is, 30X means that you must multiple the meter reading by 30 to get the same value you would get if you measured the same signal with the intensity selection set to 1X. Of course, this is true only if you do not change the position of the VARIABLE SENSITIVITY knob between measurements.

10.2 Procedure

In this experiment you will study reflection and polarization of microwaves, and measure the wavelength by generating a standing wave.



Figure 10.1: **Reflection of microwaves.** Angles of incidence and reflection are measured relative to a line normal to the plane of the reflector.

10.2.1 Reflection

- 1. Arrange the equipment as shown in Fig. 10.1, with the transmitter on the fixed end of the goniometer. Be sure that the transmitter and receiver are adjusted to the same polarity. Turn the receiver intensity selection switch to 30X.
- 2. The angle between the incident wave from the transmitter and the line normal to the reflector is the angle of incidence (see Fig. 10.1). Adjust the rotating holder so that the angle of incidence equals 45 degrees. Without moving the transmitter or the reflector rotate the movable arm of the goniometer until the meter reading is a maximum. The angle between the axis of the receiver and a line normal to the plane of the reflector is called the angle of reflection. Measure and record the angle of reflection for each of the angles of incidence shown in the table below. (At some angles the receiver will detect not only the reflected wave but also the wave coming directly from the transmitter giving misleading results. Determine the angles for which this is true.)

iiieasa	ing the angle of fen	eetioni
	Metal reflector	Plastic reflector
Angle of incidence	Angle of reflection	Angle of reflection
20°		
30°		
40°		
50°		
60°		
70°		
80°		
90°		



Figure 10.2: **Polarization.** The electric vector of polarized waves remains aligned with the diode (left). The receiver diode will only detect the component of the incident field that is aligned with it (right).

3. Replace the metal reflector with the partial reflector made of plastic and repeat the measurements.

10.2.2 Polarization

The microwave radiation from the transmitter is linearly polarized along the axis of the diode; that is, as the radiation propagates through space, its electric vector remains aligned with the axis of the diode. If the transmitter diode is aligned vertically the microwave radiation is also polarized vertically, as shown in Fig. 10.2 (left). If the detector diode were at an angle to the transmitter diode, as shown in Fig. 10.2 (right), it would only detect the component of the incident electric field that was aligned along that axis.

1. In this part of the experiment you will investigate how a polarizer can be used to alter the polarization of microwave radiation. Place the detector opposite to the transmitter. Loosen the hand screw on the back of the receiver and rotate the receiver in increments of 10 degrees until you reach 180 degrees. At each position record the meter reading. Record your measurements in the table below.

Polarization measurements					
Meter reading	Angle of receiver	Meter reading			
	10°				
	30°				
	50°				
	70°				
	90°				
	110°				
	130°				
	150°				
	170°				
	Polarization 1 Meter reading	Polarization measurements Meter reading Angle of receiver 10° 10° 30° 30° 70° 90° 110° 130° 110° 130° 110° 130° 110° 130°			



Figure 10.3: **Polarization measurements.** A polarizer is placed between the transmitter and the receiver.

- 2. Set up the equipment as shown in Fig. 10.3, and reset the angle of rotation of the receiver for vertical polarization. With the slits of the polarizer aligned horizontally, find the orientation of the receiver for which the meter will show the minimum deflection.
- 3. Repeat this measurement with the slits aligned at about 22.5, 45, 67.5 and 90 degrees with respect to the horizontal.

10.2.3 Standing waves

When two waves meet in space, they superimpose, so that the total electric field at any point is the sum of the electric fields of two waves at that point. If the two waves have the same frequency, and are travelling in the opposite directions, a standing wave is formed. The points where the fields of two waves cancel are called nodes; points where the oscillations are at maximum are called antinodes. The distance between two adjacent nodes (or antinodes) in the standing wave is exactly $1/2\lambda$ where λ is the wavelength of the radiation. In this part of the experiment you will measure the wavelength of microwaves generated by the transmitter.

1. Set up the transmitter and the receiver on the goniometer as close together as possible and adjust the receiver controls to get a full scale meter reading. Slowly move the receiver away from the transmitter. You should notice that beam intensity decreases with the increasing distance, but you should also be able to notice fluctuations in the meter reading. These fluctuations are due to radiation reflected from the receiver. The microwave horns are not perfect collectors of microwave radiation. Instead, they act as partial reflectors, so that the radiation from the transmitter is reflected back and forth between the two horns, diminishing in amplitude at each pass. If the distance between the transmitter and receiver diodes is equal to $n\lambda/2$, where n is an integer, then all the multiply-reflected waves entering the receiving horn will be in phase with the primary emitted wave. When this occurs, the meter reading will be a maximum. Therefore, the distance between two adjacent positions where a maximum will be seen is $\lambda/2$.

2. Slide the receiver one or two centimeter along the goniometer arm to obtain a maximum meter reading. Record the initial position of the receiver on the metric scale of the goniometer. While watching the meter, slide the receiver away from the transmitter, until the receiver has passed through at least 10 positions at which you see a minimum meter reading, and return to a position where the reading is a maximum. Record the new position of the receiver. Use the data to calculate the wavelength of the microwave radiation. Repeat the procedure and recalculate the wavelength. Use the formula

$$v = \lambda \nu \tag{10.1}$$

to calculate the velocity of microwave propagation in air. ν is the frequency of the microwave radiation used in the experiment, 10.5 GHz.

ATTENTION: If you decide to use Excel remember that its trig functions work only in radians and angles measured in degrees must be converted first to radians.

10.3 Report

In the report answer the following questions:

- 1. What relationship holds between the angle of incidence and the angle of reflection? Does this relationship hold for all angles of incidence?
- 2. In determining the angle of reflection, you measured the angle at which a maximum meter reading was found. Can you explain why some of the wave was reflected into different angles? How does it affect your answer to question 1?
- 3. How does reflection affect the intensity of microwave? Is all the energy of the wave that strikes the reflector reflected? What has happened to the missing energy?
- 4. Graph the data from the polarization measurements. If the meter reading, M, were proportional to the component of the electric field, E, along its axis, then the meter reading would be given by the relationship $M = M_0 \cos \theta$ is the maximum reading of the meter. If the intensity of a wave is proportional to the square of the electric field (e.g.; $I = kE^2$), then the meter reading would be given by $M = M_0 \cos^2 \theta$. Plot both functions ($\cos \theta$ and $\cos^2 \theta$) on the same graph as your experimental data and discuss the relationship between the meter reading and the polarization and magnitude of the incident microwave.
- 5. Explain how the polarizer affects the incident microwave.
- 6. Estimate the error of your speed of light measurement. Compare calculated speed of light with the textbook value and discuss possible sources of error.

Lab 11 Spherical Lenses

11.1 Introduction

Similar to spherical mirrors, the characteristics of the images formed by spherical lenses can be determined graphically or analytically. The rays for the graphical method are illustrated in the ray diagrams in Fig. 11.1. The ray that passes through the center is not deviated. The parallel ray, is refracted so that it passes through the focal point on transmission through the lens. The ray that goes through the focal point is refracted by the lens and continues parallel to the optic axis. In the case of a concave lens, the ray appears to have passed through the focal point on the object side of the lens. If the image is formed on the side of the lens opposite to that of the object, it is real and can be observed on the screen. However, if the image is formed on the object side of the lens, it is virtual.

The lens equation, which applies only to thin lenses, for analytically determining the image, is identical to that for spherical mirrors. The sign convention for the focal length, f, is positive (+) for convex or converging lenses and negative (-) for concave or diverging lenses.

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f},$$
(11.1)

where d_o is the distance between the object and the lens, d_i the distance between the image and the lens, and f, the distance between the lens and the focal point F, is the focal length.

Magnification, M, is defined as the image height, h_i , divided by the object height, h_o , and it is related to the distances d_o and d_i as follows

$$M = \frac{h_i}{h_o} = -\frac{d_i}{d_o}.$$
(11.2)

M can be negative indicating an inverted image.

11.2 Procedure

On the table top you will find an optical bench with the metric scale to measure positions of elements mounted on the bench. The light source, the screen, and two adjustable lens holders can slide along the bench when you squeeze tabs at the bases of those elements. Below are descriptions of four experiments. The TA will select two or three experiments to be completed by the students.



Figure 11.1: **Ray diagram.** A ray diagram showing the three principle rays going through a converging lens.



Figure 11.2: Measuring focal length. The optical bench with the light source, lens and screen is used for measuring the focal length of the lens.

11.2.1 Converging lens

In this part, you will determine the focal length of a lens provided by the TA by measuring several pairs of object and image distances and plotting $1/d_o$ versus $1/d_i$.

- 1. Place the light source and the screen on the optics bench 1 m apart with the light source's crossed arrow object toward the screen. Place the lens between them, see Fig. 11.2.
- 2. Starting with the lens close to the screen, slide the lens away from the screen to a position where a clear image of the crossed-arrow object is formed on the screen. Measure the image distance and the object distance. Record these measurements (and all measurements from the following steps) in the table below.

Focal length measurements



Figure 11.3: Magnification measurement. You can use any of the reference lines to measure object or image sizes.

Distance from	d_o	d_i	$1/d_o$	$1/d_i$	Image size	Object size
source to screen						
100 cm						
100 0111						
90 cm						
50 6111						
80 cm						
00 0111						
70 cm						
70 СШ						
60 cm						
00 Cm						
50 cm						
50 CIII						

- 3. Measure the object size and the image size for this position of the lens.
- 4. Without moving the screen or the light source, move the lens to a second position where the image is in focus. Measure the image distance and the object distance.
- 5. Measure the object size and image size for this position also. Note that you will not see the entire crossed-arrow pattern. Instead, measure the image and object sizes as the distance between two index marks on the pattern (see Fig. 11.3 for example).
- 6. Repeat steps 2 and 4 with light source to screen distances of 90, 80, 70, 60, and 50 cm. For each light source-to-screen distance, find two lens positions where clear images are formed.



Figure 11.4: **Telescope.** A telescope consists of two converging lenses that magnify the object.



Figure 11.5: Telescope setup.

11.2.2 Telescope

A telescope consists of two converging lenses, as shown in Fig. 11.4. In this setup you will use 100 mm and 200 mm lenses. The magnification of the two lens system is equal to the product of the magnifications of the individual lenses

$$M = M_1 M_2 = \left(-\frac{d_{1i}}{d_{1o}}\right) \left(-\frac{d_{2i}}{d_{2o}}\right).$$
(11.3)

- 1. Tape the paper grid pattern to the screen. It will serve as an object. The +200 mm lens is the objective lens while the +100 mm lens is the eyepiece. Place the screen and the lenses near the opposite ends of the optical bench, as shown in Fig. 11.5
- 2. Put your eye close to the eyepiece lens and look through both lenses at the grid pattern on the screen. Move the objective lens to bring the image into focus.
- 3. In this step, you will adjust your telescope to make the image occur in the same place as the object. To do this, you will look at both image and object at the same time and judge their relative positions by moving your head side to side. If the image and object are not in the



Figure 11.6: Parallax. Image lines are shifted relative to the object lines.

same place, then they will appear to move relative to each other. This effect is known as parallax. Open both eyes. Look with one eye through the lenses at the image and with the other eye past the lenses at the object (see Fig. 11.5 (bottom)). The lines of the image (solid lines shown in Fig. 11.6) will be superimposed on the lines of the object (shown as dotted lines in Fig. 11.6). Move your head left and right or up and down by about a centimeter. As you move your head, the lines of the image may move relative to the lines of the object due to the parallax. Adjust the eyepiece lens to eliminate parallax. Do not move the objective lens. When there is no parallax, the lines in the center of the lens appear to be stuck to the object lines.

4. Record the positions of the lenses and the screen in the table below. Measure d_{o1} , the distance from the object (paper pattern on screen) to the objective lens. Determine d_{i2} , the distance from the eyepiece lens to the image. Since the image is in the plane of the object, this is equal to the distance between the eyepiece lens and the object (screen). Remember that the image distance for a virtual image is negative.



Figure 11.7: Diverging lens. The diverging lens produces virtual images.

Telescope measurer	ments.
Position of the objective lens	
Position of the eyepiece lens	
Position of the screen	
Observed magnification	
d_{o1}	
d_{i2}	
d_{i1}	
d_{o2}	
Calculated magnification	
Percent difference	

5. Estimate the magnification of the telescope by counting the number of object squares that lie along one side of one image square. To do this, you must view the image through the telescope with one eye while looking at the object with the other eye. Remember that magnification is negative for an inverted image. Record the observed magnifications in the table.

11.2.3 Diverging lens

In this experiment, you will study virtual images formed by a diverging lens. A virtual image cannot be viewed on a screen. It forms where the backwards extensions of diverging rays cross. You can see a virtual image by looking at it through a lens or mirror. Like all images, a virtual image formed by a lens or mirror can serve as the object of another lens or mirror.

- 1. Place the -150 mm lens on the bench at the 30 cm mark.
- 2. Place the light source at the 10 cm mark with the crossed-arrow object toward the lens.
- 3. Record the object distance d_{o1} , the distance between the light source and the lens.
- 4. Look through the lens toward the light source, see Fig. 11.7. Describe the image. Is it upright or inverted? Does it appear to be larger or smaller than the object?
- 5. Place the +200 mm lens on the bench anywhere between the 50 cm and 80 cm marks. Record the position.



Figure 11.8: **Diverging lens setup.** Use of a converging lens in conjunction with a diverging lens will produce a real image.

6. Place the viewing screen behind the positive lens (see Fig. 11.8). Slide the screen to a position where a clear image is formed on it. Record the position. The real image that you see on the screen is formed by the positive lens with the virtual image (formed by the negative lens) acting as the object. In the following steps, you will discover the location of the virtual image by replacing it with the light source. Remove the negative lens from the bench. What happens to the image on the screen? Slide the light source to a new position so that a clear image is formed on the screen. (Do not move the positive lens or the screen.) Write the bench position of the light source. Adjust to focus the image. Please note that the position of the light source is identical to the position of the virtual image.

11.3 Report

In your report, discuss the following:

1. Converging lens:

- a. Plot $1/d_o$ versus $1/d_i$. Find the best linear fit, y = b + mx. The y-intercept gives directly the 1/f value. The x-intercept also gives the 1/f value. Compare the two values of f and calculate the average focal length. Are these two values equal? If they are not, what might account for the variation?
- b. Calculate magnification M from Eq. (11.2). Compare the ABSOLUTE vales of M for the two locations of the lens.
- c. Is the image formed by the lens upright or inverted? Is the image real or virtual? How do you know?
- d. Explain why, for a given screen-to-object distance, there are two lens positions where a clear image forms.
- e. By looking at the image, how can you tell that the magnification is negative?

2. Telescope:

- a. Calculate d_{i1} using d_{o1} and the focal length of the objective lens in Eq. (11.1).
- b. Calculate d_{o2} by subtracting d_{i1} from the distance between the lenses.
- c. Calculate the magnification using Eq. (11.3). Calculate the percent difference between the calculated magnification and the observed value.

d. Is the image inverted or upright? Is the image that you see through the telescope real or virtual?

3. Diverging lens:

- a. Calculate the virtual image distance d_{i1} (the distance between the negative lens and the virtual image). Remember that it is a negative.
- b. Calculate the magnification. Is M positive or negative? How does this relate to the appearance of the image?
- c. How do you know that the current position of the light source is identical to the position of the virtual image when the negative lens was on the bench?

Lab 12

Reflection and Refraction

12.1 Introduction

12.1.1 Reflection

When light strikes the surface of a material, some of the light is reflected. The reflection of light rays from a plane surface like a glass plate or a plane mirror is described by the law of reflection: "The angle of reflection is equal to the angle of incidence", or

$$\theta_i = \theta_r. \tag{12.1}$$

These angles are measured from a line perpendicular or normal to the reflecting surface at the point of incidence, Fig. 12.1 (left).

12.1.2 Refraction

When light passes from one medium into an optically different medium at an angle other than normal to the surface, it is "bent" or undergoes a change in direction, as show in Fig. 12.1 (right). This is due to the different velocities of light in the different media. For θ_1 , the angle of incidence, and θ_2 , the angle of refraction, we have

$$\sin \theta_1 = \frac{v_1 t}{d}$$

$$\sin \theta_2 = \frac{v_2 t}{d}$$
(12.2)

or

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1 t}{v_2 t} = n_{12},$$
(12.3)

where the ratio of velocities is called the relative index of refraction. For light travelling initially in a vacuum, the relative index of refraction is called the absolute index of refraction or simply the index of refraction, and

$$n = \frac{c}{v},\tag{12.4}$$

where c is speed of light in a vacuum and v the speed of light in the medium. Snell's Law can then be written

$$n_1 \sin \theta_1 = n_2 \sin \theta_2, \tag{12.5}$$

where n_1 and n_2 are the indices of refraction of medium 1 and 2, respectively.



Figure 12.1: **Reflection and refraction.** When light strikes a material, some of the light is reflected (left) and some is refracted (right).

12.2 Procedure

You will do three different experiments, listed below as A, B, and C. You may use a photometer and the fibre optic probe (recommended) or use your eye to detect maximum intensity of light. The laser or an incandescent light source can also be used in all three methods. When the laser is used no aperture mask is then needed. If you decide to use the laser, do not look into the beam. Observe reflected and transmitted light using a piece of paper. Detect the position of the laser beam using a light detector and fibre optics.

12.2.1 Angles of Incidence and Reflection

- 1. Position the incandescent light source on the left end of the optical bench, and place the angular translator about 25 cm from the end of the light source housing (or the laser). Make sure the 0° and 180° marks lie on a line parallel to the bench. Finally adjust the rotating table so that the scored lines run perpendicular and parallel to the bench.
- 2. Attach the aperture mask to the standard component carrier and place it between the light source and angular translator so that the mask is d centimeters from the center of the translator. The distance d (about 6.5 cm) is the measured distance from the center of the angular translator to the first analyzer holder on the movable arm (See Fig. 12.2).
- 3. Center the viewing screen on the special component carrier (a shorter magnetic holder) designed for use with the angular translator. Place the assembly on the rotating table of the translator so that the front surface of the viewing screen coincides with the scored line on the table, which runs perpendicular to the optical bench.
- 4. Now switch on the light and adjust the aperture mask's position (don't move the component carrier), until the entire image is on the viewing screen. With the aid of the millimeter scale marked on the screen, center the image horizontally.



Figure 12.2: **Experimental setup.** The aperture mask should be placed between the light source and angular translator so that the mask and holder are equidistant from the special component carrier.

- 5. Now replace the viewing screen with the flat surface mirror such that the mirror surface coincides with the perpendicularly scored line.
- 6. Rotate the table a set number of degrees (for example, 30°), and then move the arm until the reflected image is centered on the aperture of the viewing arm. Record the angle which the arm makes with the mirror. Repeat for 10 various settings of the rotating table. What is the relation between the angle of incidence and the angle of reflection? (Angle of incidence is the angle the incident ray makes with the normal to the reflecting surface; similarly for the angle of reflection.)

12.2.2 Index of Refraction: Part I

- 1. Take a square piece of paper about 5 centimeters on a side with a millimeter scale across the middle.
- 2. Using the same equipment set-up as in Experiment 1, put the paper between the glass plate and the special component carrier on the angular translator. The magnetic surface will hold the glass plate and paper in place. The millimeter scale should run horizontally.
- 3. Adjust the position of the special component carrier until the back surface of the glass plate coincides with the perpendicularly scored line on the table.
- 4. With the glass plate sitting perpendicular to the bench, adjust the position of the aperture mask so that one vertical edge of the image on the paper lines up with the scored line on the table which is parallel to the bench. If the glass does not alter the lights' path, the vertical edge which was centered should remain centered although the translator's table is rotated. When you use the laser observe the position of the center of the beam.
- 5. Rotate the table and record what happens to the previously centered beam. Is the incident ray refracted toward or away from the normal to the glass? Figure 12.3 shows how to calculate



Figure 12.3: **Refraction by a plate.** The incident beam is refracted through the glass plate. Note that $\sin \theta_2 \approx d/t$.



Figure 12.4: Secondary reflections.

the index of refraction given the angle of rotation and the edge displacement of the image. Using this method, a large error is introduced since the triangle formed by the refracted beam, glass surface and the normal is not a right triangle. Since the measured value of θ_2 is not accurate the index of refraction calculated from $n = \sin \theta_1 / \sin \theta_2$ can be treated at best as a first approximation. The method described below gives more accurate results.

6. Replace the glass plate with the acrylic plate and determine the index of refraction for acrylic.

12.2.3 Index of Refraction: Part II

1. With the glass plate perpendicular to the bench and the paper with the millimeter scale on it, put the screen on the viewing arm. Rotate the table to a convenient angle. Light is refracted toward the normal when passing from air to glass. Is the same true when light propagates from glass to air? By observing the positions of the image on the viewing screen, you can see that the refraction must be away from the normal at a glass-air interface. (See Fig. 12.4).
2. There should be at least two reflected images from the plate. Measure the distance between them (i.e. between their centers). You can measure the distance between the two images observed on the back of the plate using the paper with the millimeter scale or in the front of the plate on the screen placed on the viewing arm. Then if D is the distance separating them, t is the plate thickness, θ_1 is angle of incidence, and θ_2 is angle of refraction, we have

$$\tan \theta_2 = \frac{D}{2t}.\tag{12.6}$$

Calculate θ_2 for various θ_1 . Then calculate *n* from $n = \sin \theta_1 / \sin \theta_2$.

3. Repeat both methods with the acrylic plate.

12.3 Report

ATTENTION: If you decide to use Excel remember that its trig functions work only in radians and angles measured in degrees must be converted first to radians.

Present the data in the form of a table. In the discussion answer all the questions asked in section 2. In the introduction discuss total internal reflection and its applications.