Augmenting the Physics 1121 – Principles of Physics: Electricity and Magnetism Curriculum

An Interactive Qualifying Project Report

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

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Date: Thursday, December 16, 2004

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Abstract

The goal of this project was to augment the laboratory curriculum for PH1121. The existing laboratory instructions needed revision because they were unclear and disorganized. The existing curriculum lacked an experiment involving magnetostatics. Replacement laboratory instructions were created for both existing experiments. A new experiment involving the magnetic field created by a solenoid was designed and implemented into the curriculum. Student response was used to further revise and improve the new material.

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1. Introduction

Upon completion of the Physics 1121 – Principles of Physics: Electricity and Magnetism course (hereafter referred to as PH 1121), our group found that the laboratory experiments were lacking in clarity and that there was no lab work concerning magnetic fields. For the preexisting labs, the majority of the class found the procedural instructions ambiguous and the analysis required for credit unclear. Often a large group of students from the class were found in the lounge comparing interpretations of analysis instructions, trying to figure out what should be turned in and how to perform the required calculations. This was our motivation for the focus of this project. Initially, we had proposed to rewrite the instructions for the existing labs, design a quantitative magnetic field lab, and incorporate a series of demonstrations into the lecture structure. There have been numerous studies concerning the manner in which many different aspects of physics are taught[8]. Those studies which focus on laboratory exercises have shown that informative laboratory experiments improve students' performance in lecture based courses, especially for those students in the intermediate grade range[5].

The instructions for the two existing labs, one on the potential difference across two charged plates of varying configuration, and one on basic resistor circuits, needed to be redesigned to clarify both the lab procedures and the theoretical concepts. The time that students spend preparing their lab reports should be used for data analysis and interpretation, not trying to deduce how they are expected to analyze and interpret their data. We needed to write a step by step procedure so that the experiments could be performed without any time being wasted due to ambiguity in the instructions of how to set up the apparatuses and collect the data. We incorporated data sheets into the instructions to elucidate the data analysis - essentially these were fill-in-the-blank type tables where each column was a new calculation step towards the desired results, followed by conceptual questions and applicable data plots. Also, a pre-lab problem set concerning the calculations required for each experiment was designed to better facilitate understanding of underlying theoretical concepts. We hoped to encourage better comprehension of the experiments by requiring practice with the inherent concepts. Research has shown that many physics instructors feel that their students lack sufficient ability in translating physical quantities into mathematical expressions[1]. Also, students have expressed that they prefer, and gain more insight from, performing an experiment or watching a demonstration when they have already developed a strong theoretical understanding of the relevant physical phenomena[1], and research has shown clearly that students whose understanding of an experiment allows them to predict the outcome before performing it learn more effectively from the experience[2].

We also wanted to design an experiment involving magnetic fields to improve the curriculum of the PH 1121 course, since there was already a significant amount of coursework relating to magnetic fields, and yet no accompanying experiment to give students a demonstration of the phenomenon. As in the previous cases, we intended to design a lab instruction set that would be clear and easy to use, as well as a pre-lab problem set to familiarize the students with the subject matter.

We had also hoped to design a few lecture demonstrations to add to the PH 1121 curriculum; however, we underestimated the amount of time we would need to get the three experiments ready, and decided to cut the demonstrations out of our project.

1.1 Brainstorming a New Experiment

In our efforts to improve the lab curriculum for PH 1121, we had decided we would want to add an entirely new experiment. The existing curriculum only contained two experiments, and there was plenty of time in the schedule for a third. After speaking with several members of the department about the deficiencies in the existing lab curriculum, it was quite clear that what was needed was a new experiment which would give the students a chance to work with magnetic fields in a quantitative way. The core curriculum for the course covered a fair amount of material on the topic of magnetic fields, and we felt that adding an experiment where the students get to test out their new understanding of the subject in a laboratory setting would enhance their learning experience[1].

The next, and perhaps most daunting, task we would have to undertake was to design and implement an entirely new experiment which would involve magnetic fields. We discussed a number of ideas with our project advisors and other members of the physics department. We discussed designing an experiment wherein the students would be able to take quantitative measurements of the magnetic force - perhaps using a spring and a solenoid. There was also a suggestion for a magnetic inductance experiment which would have involved spinning a loop of wire in a strong magnetic field to create a measurable AC current in the loop or spinning a natural magnet at a constant angular velocity inside a coil of wire to create measurable DC current. Ultimately we settled on an experiment which lends insight into the behavior of the magnetic field itself. Most students have seen applications of the magnetic force before reaching the college level, so the spring solenoid experiment was passed over (although our final setup does involve solenoids, and it might be possible to expand this experiment at a later time to include a spring force or induction section). We liked the idea of a magnetic inductance experiment, but the first apparatus we built failed to demonstrate the phenomenon - probably because the magnitude of the magnetic field we were trying to use was far too small. The experiment that we finally decided to go with was another setup with a solenoid, wherein the students would use an external magnetic field to measure the magnitude of the ambient magnetic field in the lab room. Another great thing about this experiment was the cheap price tag. Using power supplies that the department already had available, we were able to create 15 fully operational lab stations for less than $200. All we needed were some home-made solenoids, a handful of compasses, and some wood for tables.

2. Pre-Lab Problem Sets

A significant problem with the teaching of physics to students is that many have not had sufficient experience working mathematics symbolically rather than numerically[1]. Also, the combination of multiple equations is not often recognized as the way in which to solve a problem unless practiced repeatedly in various situations[1]. In the design of the pre-lab problem sets we required more practice with these concepts so that the students entering the lab will have a sound theoretical background with the material and can focus their attention on using the correct procedure and recording their observations.

These problem sets are accompanied by fully-worked solution guides which thoroughly explain the process by which the problems are solved. Ideally, if there was some confusion with the problems they would be cleared up by the time the experiment was to be preformed. These problem sets and the accompanying solution guides are shown in Appendices A through C.

2.1 Voltage Experiment (Appendix A)

The pre-lab for the voltage experiment – designed by Cai Waegell, was intended to give the students some practice with the relationship between the electric field, electric potential, charge and distance. Also, symbolic answers were required to show that the students understood the concepts and how the equations were generated, rather than just plugging numbers into given equations. The first problem involved two point charges a certain distance from a field point, students were asked to derive expressions to define the electric field and potential at the point. Using the symbolic expression they found, they were to find a numerical answer given some conditions, sketch the direction of the field vectors, and answer a conceptual question. The second question was similar to the first except that it involves two line charge instead two point charges. The electric field and potential along the y axis were required to be expressed symbolically. The next question again expanded the dimensions of the charge as an infinite plane, which necessitates the use of Gauss' Law to determine the expression for the electric field as a function of distance. The fourth problem used Gauss' Law on a pair of infinitely long charged coaxial cylindrical shell with the radius varying in relation to the distance from the surface; the students were also asked to determine the capacitance per unit length.

Following the completion of this problem set the students were given access to the solution set that fully explained the process by which the answers were found. Students that fully understood every aspect of the problem set should have had no problems understanding the concepts underlying the experiment. If the student had some problems, the solution set should have helped, at least enough to know which questions to ask of the instructor.

2.2 Circuit Experiment (Appendix B)

The pre-lab problem set for the circuit lab was designed by Sumeet Sharma to give the students practice with Kirchoff's Voltage Law (KVL) and Charge Law (KCL) prior to performing the experiment. This will enable them to make accurate predictions about the circuits they will be designing. There were three pre-lab questions, which involved a circuit with resistors in series, in parallel, and a combination of parallel and series resistors. In the lab experiment the students will be working with similar circuits. The difference between pre lab and the lab experiment will be that during the lab session they will be using light bulbs as resistors. From the pre lab the students will be able to deduce P=VI. If there is more voltage or current across the light bulbs they will be brighter than light bulbs with less voltage or current. The pre-lab questions will prepare them to make these predictions during the lab experiment.

From the analysis of the pre-lab circuit of resistors in parallel and in series the students will be able to make a prediction about the outcome for each configuration in the actual experiment. When the light bulbs are in series there will be less current through them compared to light bulbs in parallel, therefore they will be less bright. The students will be able to make this prediction using either KCL or KVL and the pre-lab questions will give them practice with these equations. The students will be given the pre-lab answer sheet prior to performing the experiment, so that if they have any difficulty answering the questions, the answer sheet will guide them through the necessary steps.

2.3 Magnetic Field Experiment (Appendix C)

We wanted to give the students a chance to familiarize themselves with the fundamentals of the experiment. We created a pair of warm-up problems designed to walk the students through the derivations of the equations they would need to complete the lab from physics they have already learned in lecture. The first problem – designed by Sumeet Sharma and Cai Waegell, is a calculation of the magnetic field along the axis of a single loop of wire directly from the Biot-Savart Law. This calculation might be a little over the heads of a freshmen class, but it is at the heart of the experiment, so we thought it was important enough to include anyway. The second problem – designed by Nathan Neal, was intended to give the students practice with vector addition. The students were asked to calculate the net magnetic field of two solenoids in a given configuration at a specified field point. As usual, the warm-up set came with a detailed step-by-step solution, so that the students could follow the calculations, even if they were a bit advanced.

3. Procedure Instructions

An aspect of teaching experimentally that is often taken for granted by research is the clarity of instructions. The students must know exactly what to do in order to correctly reproduce the desired effect. This is a vital aspect of any educational supplement, since the main idea is for students to have an alternate medium for learning the relevant material. Unclear instructions cause students to waste time and effort and to become frustrated with the work.

3.1 Personal Experience

Our group's experience with the voltage lab was the catalyst that brought about the issue of this project. The instructions were ambiguous and scattered throughout multiple non-sequential pages. The students were given a choice of multiple configurations which makes grading the write-up more difficult on the teacher's assistant as well as adding to the chaos in the lab room. There were three different authors contributing to the instructions, so the terminology and organization changed repeatedly.

When we performed the circuit experiment we had little trouble interpreting the procedural instructions. We did, however, notice that there some of the instructions - particularly those for the first day, were poorly organized. The prediction questions were located in seemingly random sections of the instructions, and were difficult to follow chronologically while performing the experiment.

Nathan Neal and Cai Waegell stood in as guest teacher's assistants for the magnetic field experiment. We found that the majority of the students were capable of performing the experiment independently. There were a few simple questions regarding how to align the tables, how to adjust the power supply, how to mark data points and effectively estimate uncertainties in various measurements, but this was to be expected. Overall the students seemed to have little difficulty understanding the physical phenomena or performing the experiment.

3.2 Revisions

Both of the existing labs required some revision, the voltage lab more so than the circuit lab. This was the most straightforward aspect of this project because, through our own experience, we had developed a good idea of what needed to be changed and what should be kept.

3.21 Voltage Experiment (Appendix A)

The entire procedure instructions were rewritten from scratch by Nathan Neal and Sumeet Sharma, they were condensed and clarified. It was organized chronologically so that it could be followed easily by students while in the process of performing the experiment.

The purpose of the experiment was first summarized in a single paragraph. This allowed the students to have a grasp of why they were doing this experiment and what phenomena it would demonstrate, which is consistent with research that has shown that students should have a clear understanding of the theory behind the experiment prior to actually performing it[1].

The procedure was separated into the two different days of work and organized into a step-by-step format which could be easily followed and understood. It was accompanied by figures, some of which were kept from the original lab, some of which were taken from the 1120 version of the lab, and some of which were created by our group. The implementation of the step-by-step instructions with illustrative figures was intended to make the procedure much clearer and easier to follow in a lab setting.

3.22 Circuit Experiment (Appendix B)

There were only minor issues with the circuit lab's instructions. This lab was divided into a day one section and a day two section. The instruction set for day one was more ambiguous, disorganized and vague than the one for day two. The wordings for the prediction questions did not clearly mention what to predict. Cai Waegell and Nathan

Neal rewrote the instructions for day one in a more clear and organized format. We placed the prediction and the observation questions for each circuit along with the figures and instructions for that circuit so that the students would not have to flip back and forth through the lab instructions. We also wrote the new purpose statement, which was more clear and concise than the previous one.

The difference between the two sections of the experiment was that the day one experiment was qualitative and day two was quantitative. The instructions for day two were left unchanged because we decided they were already clear enough. The only change we made to the day two instructions was the addition of the data sheet to help the students organize their results. We believe that this data sheet will help student to collect and record data in more clear and efficient manner. Giving them the data sheet will guide them through an efficient method for recording and organizing data which could be useful in future lab courses.

3.3 Magnetic Field Experiment (Appendix C)

The procedural instructions were created by Cai Waegell with emphasis on clarity and brevity. The instructions are divided into bulleted sections, each with a few clear statements about what to do next, and usually a little about why. The students are walked through the steps necessary to perform the experiment and collect good consistent data. One of the major foci of our project was to design the procedural instructions so that the students could complete each experiment independently without unnecessary confusion.

The experiment itself is quite simple. The students are provided with a lab station and a power supply to operate it. Each station is a small wooden table with a solenoid mounted at one end such that the axis of the solenoid runs along the surface of the table. The students will tape some graph paper down to the table, with a centerline aligned with the solenoid's axis. They will then set a compass on the graph paper such that the cardinal directions are aligned with the lines of the graph paper. They then align the table so that the north needle points perpendicular to the solenoid's axis. Once these steps are complete, the students will turn on their power supplies, which will create a new magnetic field along the axis of the solenoid which is parallel to said axis. The rest of the experiment is taking measurements. The students place their compass at various points along the axis of the solenoid, and measure the angle it makes with respect to the original north direction. Using these measurements, and the formula for the magnetic field due to the solenoid, the students will set about calculating the magnitude of the ambient field in the lab room. The complete procedure for carrying out these calculations is in the actual lab instructions set we created (see Appendix C).

4. Lab Report Instructions

We created short lists of all material required to be included in the final lab reports, and added conveniently organized tabular data sheets to the accompanying lab instructions. The data sheets were included to clarify the results section of the experiments. Using the data sheets, the students know exactly what quantities to report. We felt that this would be a beneficial addition because this is a freshman level course and it will demonstrate to students a good format for presenting lab data, which should better prepare them for future experimental coursework. By presenting the results in a consistent format, we also hope to reduce the Teacher's Assistants' workload.

4.1 Personal Experience

When we got to the results section of the Voltage Experiment we were completely at a loss about what to do. There were questions scattered throughout the instructions, some of which were not even separated from the procedure, the plots were only briefly mentioned and not described at all, despite the fact that they were a major part of the analysis, and the values required to be reported were not stated. We spent more time trying to figure out what to do rather than actually doing the experiment and analysis. We also learned of numerous other students in the class having similar difficulties.

In the circuit experiment there was no clear format for organizing data. We were asked to answer a few theoretical questions and to record our predictions and observations. The instructions were scattered and redundant. We were expected to turn in data sheets from the lab day but there was no quantitative analysis of the data. We felt that the experiment lacked depth, and that it could be dramatically improved with a little revision.

In preparation for the day when the PH 1121 class would perform the new experiment (see Appendix C) we took some sample data to make sure that everything was in good working order. Dr. Steven Jasperson[3] has been running the sophomore laboratory course for many years and has a good grasp the finer points of experimentation in a laboratory classroom setting. We sat down with him and went over the procedure for performing the experiment in the hopes that he could lend us insight or catch something that we had missed. In preparing their lab reports, the students are asked to create a scatter-plot of B_S, the magnetic field due to the solenoid, versus the cotangent of theta, where theta is the angle of the compass needle with respect to polar north. Dr. Jasperson noticed that because the cotangent function goes to infinity at 90°, calculations involving theta and its uncertainty when theta is near 90° might create problems with the data analysis, especially since freshman students probably would not know how to interpret the discrepancy. This property of the cotangent function could create an uncertainty many orders of magnitude greater than it should be. As a result of his observation, we were able to warn the students of the potential for this problem, and to instruct them to neglect the data points where theta was close to 90° in their final calculation of the ambient field and when constructing their graphs. Since the underlying purpose of our project was to create a clear lab set, catching this problem before it created confusion among the students was very fortunate.

We also noticed that, because the magnetic field drops off so quickly as the distance from the solenoid increases ($B_S \sim 1/z^3$), and the cotangent function goes from zero to infinity over a region of 90°, that the quantities the students were asked to graph covered a range of at least 3 orders of magnitude. We discussed the possibility of having the students construct their graphs on logarithmically scaled graph paper, but Dr. Jasperson felt that this was a little too confusing and time-consuming for a freshman laboratory course. Instead, we decided to instruct the students to include only data points in the region of a single order of magnitude, somewhere around where theta is 45°, and to scale the graph appropriately. This approach reduces the number of points the students are expected to plot on their graphs, and makes the scale and the associated error bars easier to interpret. Conveniently, this also solves the cotangent of 90° problem, as the students are not expected to graphically interpret that data at all.

4.2 Voltage Experiment (Appendix A)

The entire results section in the voltage experiment, such as it was, had to be abandoned and replaced. A separate section with clear instructions of what needed to be included in the lab report was created by Nathan Neal, as well as clear instructions of what graphs to construct and how to go about formatting them. The lab instructions include organized data tables relating to each section of the experiment. This setup was intended to make the construction of the graphs of experimental data versus theoretically predicted values easier. Having the data laid out in a tabular form provides insight into the behavior of the system and the physical phenomena at work in much the same way that graphs do.

4.3 Circuit Experiment (Appendix B)

There was no quantitative data to be analyzed from the first day of this experiment, so all that was required for this part was predictions and observations and some conceptual "what if" questions. This section of the experiment was designed to demonstrate the phenomena, not to provide actual data. The second day implemented the use of digital multi-meters so that the students could collect actual experimental measurement data for the voltage, current, and resistance across each component. The students were asked to organize their data in a table that Cai Waegell and Nathan Neal designed, to calculate the error in their final results with respect to the theoretical values, and to make sure they were within the tolerance given with the resistors. The data sheet was the only new component added to this section, the questions for the first day were reworded and reorganized in the instructions. These were simple revisions which we feel greatly increase the clarity of the laboratory instructions, and simplify the format for the final lab reports the students would be handing in, which should benefit both the students and the graders. We didn't feel that anything else needed to be changed.

4.4 Magnetic Field Experiment (Appendix C)

The lab report instruction set for the magnetic field mapping experiment was created by Cai Waegell. These instructions were also designed with emphasis on clarity and brevity. The students had already been instructed to collect and analyze various data, and to estimate uncertainties in their measurements along the way. We had decided that one of the goals of this lab report would be to give the students an introduction to the rigors of experimental uncertainty and error analysis. The faculty we discussed this with agreed that the calculations necessary to propagate the uncertainties through the formulas the students would be using to interpret their data were too difficult to require of freshmen[3,6,7]. The solution we came up with was a Microsoft Excel spreadsheet designed to help the students with their data analysis. The spreadsheet is completely set up so that all the students need do is enter in the data they recorded – measurements and their respective uncertainties, and all of the difficult and cumbersome calculations would be performed for them. The spreadsheet is set up to propagate uncertainties through the calculations it performs and return values for the uncertainty of calculated quantities. The students are instructed on how to draw error bars onto their graph, how to create best fit lines to their data, and how to interpret these best fit lines to determine the uncertainty in their final measurement – the magnitude of the ambient magnetic field in the lab room. Overall we hoped to give them a feel for how uncertainties in experimental measurement can create uncertainty in the results of an experiment, and how much rigor and precision is required to perform a good experiment.

The lab report instructions also included a set of four questions. First the students are asked to use the provided equation for the magnetic field of a solenoid – one which they should have derived when solving the warm-up problems set, to calculate the magnitude of the ambient magnetic field directly from the data from a single point. The Excel sheet relieves the tedium of having to perform this calculation twenty five times, not to mention the error propagation, but we wanted to make certain the students had at least some understanding of what the spreadsheet was doing, and how much effort it was saving them. We also wanted to see how well the students understood the physical phenomenon they were studying – in this case the magnetic field of a solenoid, the second question asks about the behavior of the equation they used. One large source of uncertainty in this experiment is the fact that the equation they are using describes the magnetic field as though all of the coils of the solenoid were centered in one plane. Students have also discussed the behavior of ideal solenoids in lecture for the PH 1121 class, so the third question concerns the differences between the idealized cases and the real solenoid they used for the experiment. The fourth question is the most important.

There are a number of features of this experiment which are far less than ideal. That is, there are quite a few factors which contribute to imprecision in the experiment. One of our primary goals here was to give the students a sense for experimental uncertainties and their impact on the success or failure of an experiment, so this last question focuses on error analysis. We asked the students what aspects of the experiment and the procedure for performing it may contribute to uncertainties in their results and if their estimates for uncertainties in the various measurements they took were reasonable. This question was really just a catch-all, designed to get the students thinking about the details and limitations of the experiment and cement their understanding of it.

5. Designing the New Experiment (Appendix C)

We had settled on what experiment we were going to add to the curriculum, so the next task was to design an apparatus for the experiment which would make data collection relatively easy for the students, and which would do a good job of demonstrating the phenomenon we wanted demonstrate. We had chosen to use solenoids to create the magnetic field the students would use in the experiment because the equation which describes the magnetic field produces by a solenoid along its cylindrical axis is a relatively simple one which a freshmen class should be able to work without too much confusion. The students needed to be able to measure the field of the solenoids along their cylindrical axes in order to use the equation mentioned above, which meant the compasses they would be using to measure the direction of the net magnetic field needed to be places on those axes.

In order to facilitate this, we created small lab tables to mount the solenoids on. Each solenoid was mounted so that its central cylindrical axis lines up with the surface of the table (see Figure 5.1and 5.2). These tables also made the matter of recording the direction of the compass needle at each field point much easier. The students could tape a piece of millimeter graph paper down to each table, and align the axis of the solenoid with one of the lines on the graph paper. They could then mark the direction of the compass needle on the graph paper at each field point and worry about determining the angles later on.

One of the first things we had to do was figure out the specific parameters of the solenoids we would use. There are a number of variables that go into determining the magnitude of the magnetic field of a solenoid, and we had to find a good set of conditions such that it would create a magnetic field comparable in magnitude to that of the Earth about half way across the piece of graph paper the students would be using to collect their data. If the field from the solenoid was too strong, the Earth's field would have little effect on the direction of the compass needle, and likewise if the field of the solenoid was too weak, then the deviation from magnetic north would be difficult to measure. We wanted a field that would be several times greater than that of the Earth very near to the solenoid, but several times less than that of the Earth at the far edge of the graph paper.

We also had to consider the realistic limitations on how much current we could run through the solenoids and how much wire we would need to wrap around each solenoid - which depended on both the radius of the coil and the number of turns. We constructed a simple computer model which allowed us to adjust the various parameters and see how they would affect the field's magnitude as a function of distance from the solenoid. In the limit when the distance is much larger than the radius of the solenoid, the field drops off as an inverse cubic. We wanted the field to drop of a little less quickly than that so that the values the students would be calculating and plotting would range over as few orders of magnitude as possible. The way to accomplish this was to make the radius larger. Though the overall magnitude of the field decreases as the radius is increased, the contribution it makes in the denominator of the equation for the field of the solenoid causes the magnitude to drop off more slowly in the region where the radius is comparable to the distance from the solenoid. We settled on a radius of about five and a half centimeters, which was large enough to have the desired effect without requiring an infeasible amount of wire. With this radius, three hundred turns of wire, and between a fifth and a half of an Ampere of current, we could get the range of field strengths we were looking for. Once we had figured out all of these specifics we constructed a prototype laboratory table apparatus (see Figure 5.3) and did a few rough test runs on the experiment to make sure it was feasible.

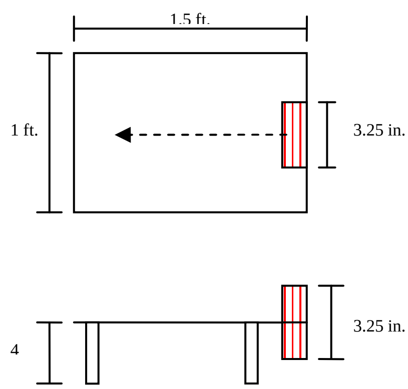

Figure 5.1

Schematic Design

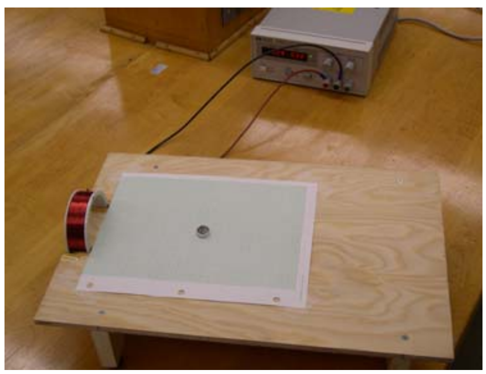

Figure 5.2

Finished Product

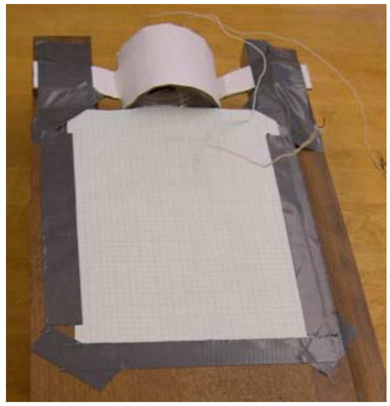

Figure 5.3

Prototype Design

Next we had to go about acquiring materials and constructing the fifteen lab stations that would be needed if the students were to perform the experiment. Roger Steele was our biggest supporter on this, and without his help I it would have been extremely difficult to have had everything ready in time. Roger helped us order the appropriate wire for the solenoids, assisted in constructing the lab tables, and was available to provide us with any sort of materials we ended up needing along the way. We got the plywood for the lab tables at Home Depot, and as an afterthought, we ended up purchasing fifteen sets of rubberized feet for them as well. The rubber feet would make the tables more stable, and would make it a little tougher to misalign them by accidentally bumping them. Since the table's alignment is essential for the collection of consistent data in the experiment, we felt this was an important addition.

The most difficult component to come up with were the fifteen solenoids, and here we have to express our gratitude to William Weir and Steve Derosier in the Washburn Machine Shops for the their assistance. We had figured out roughly how much wire we were going to need when we settled on the radius and number of turns for the solenoid, and Roger had arranged for the department to order the appropriate amount for us. Next we had to figure out how to get the right number of turns onto each solenoid. We had hoped to find a lathe or similar device which could count the number of revolutions it had been through, but as no such device existed, we concluded that the best way to proceed was to figure out how long the wire wrapped around each solenoid would have to be, and measure out fifteen appropriate lengths of wire. The length ended up being just shy of one hundred yards, so we spent an afternoon on the football field spooling out wire to the correct length and then rewrapping it onto some spare PVC pipe was had purchased at Home Depot. We were also using the PVC as the cylindrical core for our solenoids. The machinist is Washburn cut the PVC into one inch sections and then lathed a groove into the side of each piece for the wire to run in. They also wrapped the solenoids for us, and did a superb job getting the turns to be as straight and neat as we could have hoped for. Having the planes of each loop in the solenoid as close to parallel to one another as possible was important, since their were already so many other aspects of the solenoid which were less than ideal.

Once we had the solenoids ready, all that was left to do was mount them on the tables. Roger had cut notches into the side of each table where the solenoids would fit when they were centered on the edge of the table. The cylindrical axis of each solenoid needed to be as closely aligned with the surface of the table as possible, so we used measuring squares to make sure that the face of each solenoid was perpendicular to the table, and then used epoxy to affix them permanently in that orientation. At the suggestion of Professor Iannacchione[7], we also used pieces of cardboard at support struts to make the solenoids more stable, and these were affixed with epoxy as well. After that, there were only a few minor concerns left to contend with. We had to strip the ends of the wires coming from each solenoid and dig up some other connectors so that the solenoids could be connected to their respective power supplies. The day we were setting up the apparatuses for their first lab section, we realized we would have to provide the students with mm graph paper, some tape, and a few pairs of scissors so that they would have everything they needed to perform the experiment readily available.

Overall, the material costs for everything that went into creating the lab stations and providing what materials the students would need in the lab room cost less than $200. Hopefully, if nothing else, it was a cost effective contribution to the WPI physics department and academic community.

As stated above, the major emphasis of the lab report instructions was clarity and brevity. The instructions were written to be as explicit as possible without going into unnecessary detail. Unfortunately, it is difficult to judge what a group of students will find clear. We created a questionnaire for the students (see Appendix D), so that their feedback could be used to improve the lab report instructions.

We met with our project advisors[6,7] to decide what questions should be included in the survey in order to get the most useful feedback. The first three questions were designed to get a sense of the students' academic background. We hoped this information would give us insight into how students in varying fields of study and with varying levels of academic experience responded to the experiment. The fourth and fifth questions asked the students to rate their understanding of the physical phenomenon at work – magnetic fields, before and after performing the experiment. The student response to these questions was our best way to gauge how much the students themselves thought they had gained from the experience – ultimately the deciding factor in the success or failure of our new experiment. The sixth question asked the students for opinions concerning the error analysis section we had included in the Magnetic Field Mapping experiment (see Appendix C). Error analysis is often a bit too advanced for freshman classes, and we needed to know if the students found the material too confusing. We had attempted to simplify the more difficult aspects of error analysis using the Data Analysis Excel spreadsheet, but we needed to get a sense of how successful this attempt had been. We also needed to find out if the students found the inclusion of this new material too difficult to be a valuable learning tool. The seventh question asked the students what they perceived to be the objective of conducting the experiment. We hoped that the student response to this question would give us a general idea of how well the students understood the experiment and the accompanying laboratory instructions – which was also a measure of how successful our attempts at clarity had been. The eighth question asks the students if they have any suggestions for ways we can improve or revise the experiment and/or the laboratory instructions. The reasons for including this question should be self explanatory. The ninth and tenth questions were designed to get a sense of how much the students enjoy the subject matter, and how well they feel they have performed in the class. We wanted to use this information to weight the various survey responses. That is, to learn how students with varying levels of success in the course and enthusiasm regarding the subject matter responded to the previous questions. Once we had decided on our questions, the survey was posted online by the gracious Dr. Carolann Koleci, without whose help we would surely have been lost.

6. Results

We had gone through the Magnetic Field Mapping Experiment and data collection process a few times to make sure that it wouldn't take too long to be completed in a single fifty minute laboratory section, and it usually only took us about fifteen minutes, so we didn't think there would be any problem with time. Nathan Neal and Cai Waegell assisted Christopher Rehm, the TA instructor for the laboratory section, with running both sections and explaining the details of how to perform the experiment and collect data to the students. As expected, most of the students finished collecting their data within about twenty minutes, and none of them needed more than fifty minutes. A number of students had difficulty interpreting the instructions for aligning the laboratory tables and the graph paper appropriately, and a few had difficulty setting their power supplies correctly. We were able to catch most of these problems within the first ten minutes of each section, and they created no noticeable difficulty for the students, but this did raise a few questions concerning the clarity of the procedural instructions, which are addressed below.

Fifteen out of the fifty three students enrolled in the PH 1121 course filled out our online survey, which is better than twenty percent of the class, and hopefully a fair representation of how the class as a whole responded to the new experiment. Most of the students who filled out the questionnaire[9] felt that there was not enough explanation concerning the error analysis they were expected to work with. Many felt that the error analysis aspect of the lab was simply too difficult to understand without some background on the subject. A few said that the entire instruction set was unclear and poorly organized, which is probably a result of the fact that not all of the lab documentation was completely organized by the time the students performed the experiment. We were surprised at how many students found sections of the laboratory instructions set unclear, considering that clarity had been taken into the heaviest consideration when writing them.

Most of the students who filled out our survey were freshmen, with little physics background, which is probably a fairly good representation of the student background for PH 1121 in any year. There was a wider range on the academic performance question.

We got somewhat diverse responses from students who consider themselves to be at the top of their class, to students who weren't sure they would even pass, and everywhere in between, so overall the survey results represent at least a loose cross-section of the students in the class. Almost all of the students stated the objective to be about understanding the magnetic field generated by a solenoid and how uncertainties in measurements propagate throughout the calculations. Although many of them had difficulties, they all seemed to have a good grasp of the purpose and importance of the experiment.

Cai Waegell also sat in on a Math And Science Help (MASH) session, where a number of students were working on their lab reports so that any unforeseen ambiguity in the instructions could be clarified personally. This was also an opportunity to get feedback from the students personally, and to get a sense of what aspects of the instructions were causing confusion. One major problem was that the decision to truncate the graph because of the problem with uncertainties in the cotangent function was made just before the students performed the experiment, and so the revised instructions – which have since been added to the lab report instructions set, were only available in an email. Another problem that became apparent was a lack of clear definition for a few symbols that were used in the instruction set. The lowercase Greek letter Delta is used to denote an uncertainty in a measurement in the instruction set, and indeed this is quite a common notation, however a class of freshmen cannot be expected know what it means, and we failed to state it's definition explicitly. Another problem had to do with using the provided Excel spreadsheet to perform the calculations for the experiment. The formulas in the spreadsheet are designed assuming that the angle theta, of the compass needle, is measured with respect to axis of the solenoid, rather than another perpendicular axis. One of the figures that accompanies the instruction set shows theta explicitly on a diagram of the compass and solenoid configuration, however, we failed to stress the necessity of using that exact value for theta in the spreadsheet, and a number of students had measured it with respect to different axes.

There was also a significant problem with the scheduling of the new experiment. The students were only given two days to write up their lab reports, and because the lab day fell so close to the end of the term, a number of students complained that it was too much work for them to handle given the timeframe.

7. Conclusions

The various student feedback we collected has allowed us to revise the laboratory instruction set in an effort to clarify everything that the students found confusing and to make the experiment a better overall learning experience. We have attempted to resolve all of the concerns that were raised, and we feel that the revised edition of the instruction set is a marked improvement over the original.

We have gone through the new laboratory instructions and attempted to make the parts that the students found unclear more explicit. We have also defined the symbols more explicitly, so that the instructions are consistent.

A more general introduction to error analysis, and more complete explanation of its importance in experimentation has also been added into the instruction set, and hopefully it will be clear enough for students who take this course in the future.

The organizational problems we encountered were simply the byproducts of trying to assemble an entirely new experiment and implement it into the curriculum. All of those issues have since been resolved, including the addition of the supplementary instructions, to the main body of the laboratory instructions set, and everything should be organized and ready to use for next year's class.

A possible solution to the scheduling problem would be to have the lab day a week earlier by moving the entire lab schedule backwards by one week. The Mandatory Pre-Test could be moved to a conference section to free up the first week for Day One of the Voltage Experiment. The only foreseeable problem with this solution is that the students may not have been introduced to the Electrostatic Field and Electric Potential is sufficient detail to understand the fine points of the Voltage Experiment.

. It is unfortunate that this class, the first to conduct the new experiment, had so many difficulties understanding it and using the accompanying documents. This was, however, a problem we expected, since it was impossible to anticipate what the students would find unclear. This is what made the survey questionnaire such an important aspect of our project. The survey gave us a good idea of what specific aspects of the experiment and laboratory instruction were causing confusion and difficulties - essentially what ambiguities we had overlooked when putting it all together, and gave us a good basis from which to make our revisions.

In general we feel that the magnetic field experiment was a success. It demonstrates the phenomena in question and allows the students to see magnetic fields at work in a laboratory setting. It also provides a useful introduction to experimental error analysis. Even though there were some problems with this aspect of the experiment, most of the students we got feedback from appreciated the importance of error analysis, and we feel confident that, with the revised instructions, this section of the experiment will be more successful in the future. The apparatus that we designed also allows for future expansion of the experiment - possibly to include a section on magnetic induction.

We feel that the new laboratory instructions that we have created for the preexisting experiments are a marked improvement over the old ones. According to Chris Rehm, there has been less confusion overall by the students both in the lab and when preparing the reports[4], then there was for the students in PH 1120 who were using the old laboratory instructions. This suggests that the new laboratory instructions sets that we created were at lease somewhat successful, though we have no conclusive evidence to back this up – just common sense. The fact that we had performed these experiments in the same setting as the students who will take this class in the future lent us a great deal of insight into how they needed to be rewritten. The value of the pre-lab problem sets was more difficult to gauge, but since the overall response towards the lab was favorable we feel that they were a helpful addition. As mentioned above, we have also found a number or educational research publications which indicate conclusively that students who have already established familiarity with the particular theory concerning the topics of an experiment gain significantly more from the experience[1,4,5], which serves to somewhat validate the inclusion of the warm-up problems sets, even though we have no conclusive student feedback on that subject.

Overall, we think that our Interdisciplinary Qualifying Project has been a success. We feel that the synthesis of what we have added to the PH 1121 curriculum – the rewritten laboratory instructions, the warm-up problem sets, and the entirely new experiment - is a significant contribution to the WPI physics department and academic community. In completing the various goals we set for ourselves, we got a great deal of practice working as members of a group. We learned to divide up the work we would need to do and to delegate the various responsibilities of preparing new material for the PH 1121 curriculum. Each of us is focusing in a different area of study, and we were each able to offer unique perspectives on the subjects at hand. We were also able to divide and delegate the work we had to do for our project into individual sections to which each of us was best suited. This made the work we had to do for the project more efficient and allowed each of us to make a significant contribution to the project. Our work on this project also gave us a real introduction to the nature of teaching physics students in a university environment, and through the research we have done concerning the benefits of experiments in lecture courses[5], we have learned a fair amount about the ideas and conclusions of contemporary physics education researchers.

We feel that we have accomplished all of the goals we set out to accomplish when we came up with the details of this project, as well as the underlying goals of an Interdisciplinary Qualifying Project. We have put a great deal of time and effort into completing this project, and overall, we are pleased with the outcome.

Acknowledgements

We would like to thank: Dr. Carolann Koleci and Dr. Germano Iannacchione for giving us the opportunity to do this project, Roger Steele for his assistance in acquiring materials, Fred Hutson for general help getting the labs set up, William Weir and Steve Derosier for their help constructing the solenoids, and Dr. Steven Jasperson for his advice and counsel throughout the project.

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Appendix A

Voltage Experiment

- Pre-lab Problem Set
- Pre-lab Solution Guide
- New Instructions

Experiment-1 Warm-Up Problems

Problem 1

Place a point charge q at the origin of an x-y plane, and another charge -q a distance d above it on the y-axis, see Fig. 1.

a) Find an equation in x and y for the electric potential everywhere in the plane.

b) Take the gradient of your potential equation and find the electric field everywhere in the plane. $\vec{E} = -\vec{\nabla}V$

c) Now let *d* = 4 m and calculate the electric potential and the electric field (by component) at the points in the table below.

d) Plot arrows at these points on your *x* - *y* plane to show the direction of the field vectors. Next sketch freehand electric field lines onto your *x* - *y* plane. Note that the field and potential for this configuration are symmetrical with respect to the *y*-axis.

e) What can you say about the electric field and electric potential on the *y*-axis between your two charges?

X	Y	V	E_x	E_y
0	1			
0	2			
0	3			
0	-2			
0	6			
1	1			
1	2			
1	3			
1	5			
1	-1			

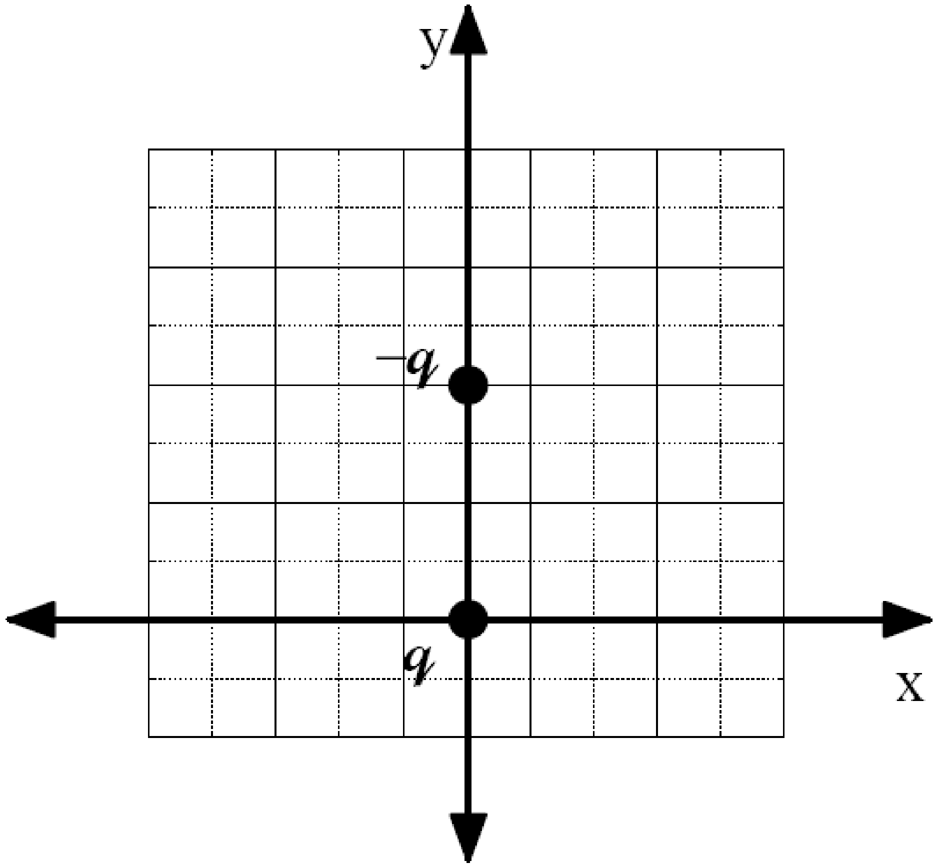


Figure 1: Configuration for Problem 1.

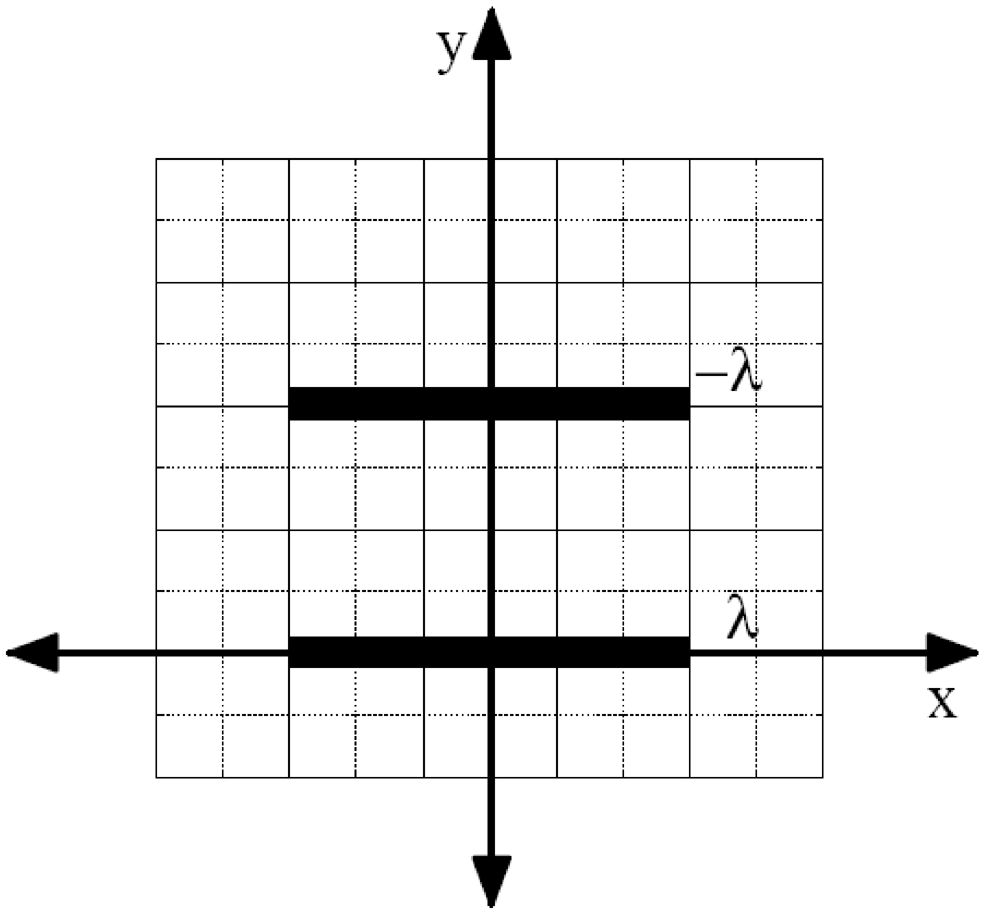


Figure 2: Configuration for Problem 2.

Problem 2

A line of charge of length L and linear charge density λ rests on the x axis with its center at the origin. Another parallel line of charge of length L and linear charge density $-\lambda$ rests with its center on the y axis a distance d above the first, see Fig. 2.

a) Find an equation in y for the electric field due to these two line charges everywhere on the y axis.

b) Find an equation in y for the electric potential due to these two line charges everywhere on the y axis.

Problem 3

An infinite plane of uniform surface charge density σ lies a distance d directly below another infinite plane of uniform surface charge density $-\sigma$
Use Gauss's Law to find the electric field above, below and between the two charged planes. Does your answer depend on d?

Problem 4

An infinitely long cylindrical shell of radius a which carries uniform linear charge density λ lies within another of radius b and uniform linear charge density $-\lambda$. The two cylinders are coaxial. Use Gauss's Law to calculate the electric field at a distance r from the center axis of the cylinders for

a) $r < a$

b) $a < r < b$

c) $r > b$

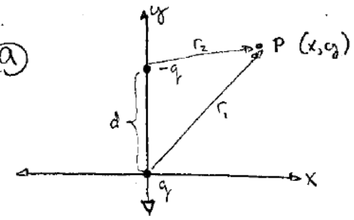
d) Calculate the potential difference between the two cylinders.

$$V = -\int_a^b \vec{E} \cdot d\vec{r}$$

e) Find the capacitance per unit length of this configuration. $q = CV$

PROBLEM # 1

(a)



$$V_1 = \frac{1}{4\pi\varepsilon_0}\left(\frac{q}{r_1}\right) \qquad V_2 = \frac{1}{4\pi\varepsilon_0}\left(\frac{-q}{r_2}\right)$$

$$V_p = V_1 + V_2 \qquad r_1 = \sqrt{x^2+y^2}\,, \quad r_2 = \sqrt{x^2+(y-d)^2}$$

$$V_p(x,y) = \frac{q}{4\pi\varepsilon_0}\left(\frac{1}{\sqrt{x^2+y^2}} + \frac{-1}{\sqrt{x^2+(y-d)^2}}\right)$$

(b)

$$\vec{E}(x,y) = -\vec{\nabla}V(x,y) = -\left\langle \frac{\partial V}{\partial x}, \frac{\partial V}{\partial y}\right\rangle \equiv \frac{-\partial V}{\partial x}\hat{x} + \frac{-\partial V}{\partial x}\hat{y}$$

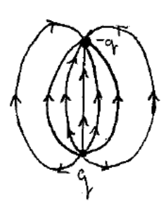
This operation is called taking the gradient of V. It takes a scalar function and returns a vector field which points in the direction of maximum increase of the scalar function.

If you've never seen partial derivatives before, they are very simple: They are identical to regular derivatives except that any variable other than the one your deriving with respect to is treated as a constant, thus...

$$\frac{\partial}{\partial x}(x^2 y) = 2xy \quad \text{or} \quad \frac{\partial}{\partial y}(x^2 y) = x^2$$

$$\vec{E} = -\vec{\nabla}V = \frac{q}{4\pi\varepsilon_0}\left\{\left(\frac{-x}{(x^2+y^2)^{3/2}} + \frac{x}{(x^2+(y-d)^2)^{3/2}}\right)\hat{x} + \left(\frac{-y}{(x^2+y^2)^{3/2}} + \frac{y-d}{(x^2+(y-d)^2)^{3/2}}\right)\hat{y}\right\}$$

(d)

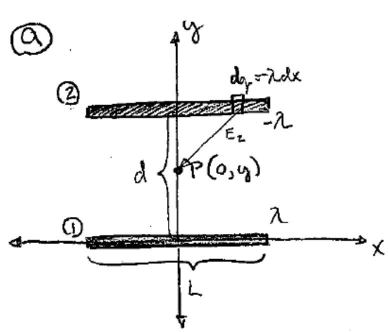


Your field diagram should look something like this. This is the electric field due to an electric dipole.

(e) You should notice that while the field is constant between the two charges, the electric potential decreases linearly from $y=0$ to $y=d$ on the y-axis.

PROBLEM # 2

(a)



$$\vec{E}_p(0,y) = \vec{E}_1 + \vec{E}_2$$

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}\hat{r}$$

$$dq_1 = \lambda dx$$

$$dq_2 = -\lambda dx$$

$$|\vec{r}_1| = \sqrt{x^2+y^2}$$

$$|\vec{r}_2| = \sqrt{x^2+(y-d)^2}$$

$$\hat{r} = \frac{\vec{r}}{|\vec{r}|}$$

$$\hat{r}_1 = \frac{-x\hat{x} - y\hat{y}}{\sqrt{x^2+y^2}}$$

$$\hat{r}_2 = \frac{-x\hat{x} - (y-d)\hat{y}}{\sqrt{x^2+(y-d)^2}}$$

$$\boxed{\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^3}\vec{r}}$$

Before you do any serious calculations, you should stop to look at the symmetry of this configuration, note that on the y-axis, the horizontal ($\hat{x}$) components of the field due to both line charges will sum zero. Thus you need only consider the y-component of the field

$$\vec{E}_1 = \frac{-\lambda\hat{y}}{4\pi\epsilon_0}\int_{-L/2}^{L/2}\frac{x\,dx}{(x^2+y^2)^{3/2}}$$

You can simplify this calculation further by noting that because of the symmetry with respect to the y-axis, the contributions from the charge on either side will be equal, thus

$$\boxed{\vec{E}(0,y) = \frac{\lambda\hat{y}}{2\pi\epsilon_0}\left(\frac{1}{\sqrt{\frac{L^2}{4}+y^2}} - \frac{1}{\sqrt{\frac{L^2}{4}+(y-d)^2}} - \frac{1}{y} + \frac{1}{y-d}\right)}$$

$$\vec{E}_1 = \frac{-\lambda\hat{y}}{2\pi\epsilon_0}\int_0^{L/2}\frac{x\,dx}{(x^2+y^2)^{3/2}} = \frac{\lambda\hat{y}}{2\pi\epsilon_0}\frac{1}{\sqrt{x^2+y^2}}\Bigg|_0^{L/2} = \frac{\lambda\hat{y}}{2\pi\epsilon_0}\left(\frac{1}{\sqrt{L^2/4+y^2}} - \frac{1}{y}\right)$$

$$\vec{E}_2 = \frac{\lambda\hat{y}}{2\pi\epsilon_0}\int_0^{L/2}\frac{x\,dx}{(x^2+(y-d)^2)^{3/2}} = \frac{-\lambda\hat{y}}{2\pi\epsilon_0}\frac{1}{\sqrt{x^2+(y-d)^2}}\Bigg|_0^{L/2} = \frac{-\lambda\hat{y}}{2\pi\epsilon_0}\left(\frac{1}{\sqrt{\frac{L^2}{4}+(y-d)^2}} - \frac{1}{y-d}\right)$$

PROBLEM 2

(b) The potential difference between two points in a region of known electric field is given by the path integral

$$V = -\int_b^a \vec{E}\cdot d\vec{l} \qquad \left\{ \underset{\text{for this problem}}{d\vec{l} = dy\,\hat{y}} \right\}$$

In order to find the total electric potential at the point $(0, Y)$ we want to evaluate the difference between $(0, Y)$ and another point where $V = 0$. The first point that comes to mind is probably $(0, \infty)$, but if you take this integral from ∞ to Y, the result will diverge and will be of no use to you. This is the trick. If you look carefully at the charge configuration in Figure 2, you will see that there is another point where the electric potential goes to zero, right in the center between the two line charges at the point $(0, d/2)$. Thus our integral takes on the form

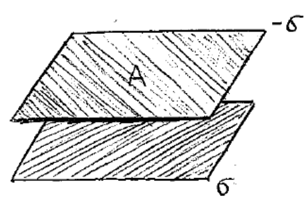
These first two integrals can be solved by trigonometric substitution.

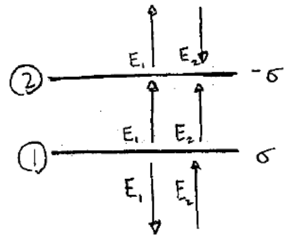
$$V = -\int_{d/2}^{Y} E\,dy = \frac{-\lambda}{2\pi\epsilon_0}\left\{ \int_{d/2}^{Y} \frac{dy}{\sqrt{\frac{L^2}{4}+y^2}} - \int_{d/2}^{Y} \frac{dy}{\sqrt{\frac{L^2}{4}+(y-d)^2}} - \int_{d/2}^{Y} \frac{dy}{y} + \int_{d/2}^{Y} \frac{dy}{y-d} \right\}$$

$$V = \frac{-\lambda}{2\pi\epsilon_0}\left\{ \ln\left| \frac{\sqrt{L^2+4y^2}}{L} + \frac{2y}{L} \right| \Bigg|_{d/2}^{Y} - \ln\left| \frac{\sqrt{L^2+4(y-d)^2}}{L} + \frac{2(y-d)}{L} \right| \Bigg|_{d/2}^{Y} - \ln|y| \Bigg|_{d/2}^{Y} + \ln|y-d| \Bigg|_{d/2}^{Y} \right\}$$

$$V(0, Y) = \frac{-\lambda}{2\pi\epsilon_0}\left\{ \ln\left| \frac{\sqrt{L^2+4Y^2} + 2Y}{\sqrt{L^2+d^2} + d} \right| - \ln\left| \frac{\sqrt{L^2+4(Y-d)^2} + 2(Y-d)}{\sqrt{L^2+d^2} - d} \right| + \ln\left| \frac{d}{2Y} + 1 \right| \right\}$$

PROBLEM 3



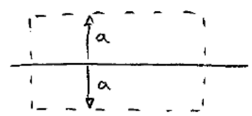


$E_1 + E_2 = 0$

$E_1 + E_2 = \frac{\sigma}{\epsilon_0}$

$E_1 + E_2 = 0$

The Gaussian surface we use to solve this problem is often called a Guassian Pillbox. First we will consider the flux through a Gaussian Pillbox of infinite length and width and finite thickness centered on the charged plane as shown below



We can now see by symmetry that the flux through the top and bottom of the box will be the same

We will also only be considering the area of the top and bottom of the box, since the area of the sides in infinitesimal.

So finally, the total area of the box = $2A$

and the total enclosed charge on the plane is σA.

Now Gauss's Law states that:

$$\oint_{\text{Surface}} \vec{E} \cdot d\vec{a} = \frac{q_{enc}}{\epsilon_0}$$

You should make sure it is clear to you that $\vec{E}$ is perpendicular to the plane everywhere - because the plane is infinite.

This allows us to restate Gauss's Law for this problem as:

$$EA_s = \frac{q_{enc}}{\epsilon_0}, \quad E = \frac{q_{enc}}{A_s \epsilon_0} = \frac{\sigma \cancel{A}}{2\cancel{A}\epsilon_0}, \quad \vec{E}_1 = \frac{\sigma}{2\epsilon_0}(\hat{z}) \rightarrow \boxed{\text{away from the plane}}$$

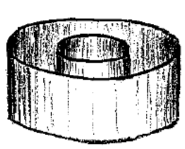
repeating this calculation for the negatively charged plane gives $\vec{E}_2 = \frac{-\sigma}{2\epsilon_0}(\hat{z})$ $\boxed{\text{towards the plane}}$

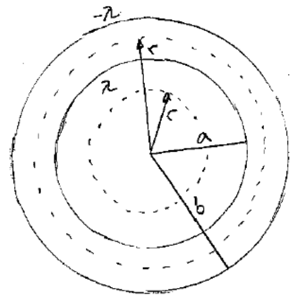
By looking at the vector diagram in the upper right you can see how the fields add together.

$$\vec{E}_{above} = \vec{E}_{below} = 0, \quad \vec{E}_{between} = \frac{\sigma}{\epsilon_0}\hat{z}$$

Notice that neither answer depends on the distance from the plate, and thus the answer will not depend on the distance between the plates. The field due to each plate is constant over all space.

PROBLEM # 4





To solve, use an infinitely long Gaussian Cylinder of radius r

You should notice first that by symmetry, the field due to an infinitely long charged cylinder is radially outward and perpendicular to the cylinder's axis, and thus it will always be parallel to the area vector. so again

$$\oint_{\text{surface}} \vec{E}\cdot d\vec{a} = \frac{q_{enc}}{\epsilon_0} \quad \text{simplifies to} \quad EA = \frac{q_{enc}}{\epsilon_0} \quad \text{or} \quad E = \frac{q_{enc}}{A\epsilon_0}$$

(a) for any r, the surface area of an infinitely long cylinder is

$2\pi r l$ (again ignoring the infinitesimal contribution of the endcaps)

(b) for $r < a$, there is clearly no enclosed charge, so $\vec{E} = 0$

(c) for $a < r < b$ the enclosed charge is λl, thus

$$E = \frac{\lambda \cancel{l}}{2\pi r \cancel{l} \epsilon_0}, \quad \vec{E} = \frac{\lambda}{2\pi\epsilon_0 r}\hat{r}$$

and finally for $r > b$, $q_{enc} = \lambda l - \lambda l = 0$, so again $\vec{E} = 0$

(d) $$V = -\int_b^a \frac{\lambda}{2\pi\epsilon_0}\frac{dr}{r} = -\frac{\lambda}{2\pi\epsilon_0}\ln|r|\Big|_b^a = \frac{-\lambda}{2\pi\epsilon_0}\ln\left|\frac{a}{b}\right|$$

(e) $$q = CV, \quad \lambda l = C\frac{-\lambda}{2\pi\epsilon_0}\ln\left|\frac{a}{b}\right|, \quad \frac{C}{l} = \frac{-2\pi\epsilon_0}{\ln\left|\frac{a}{b}\right|}$$

Note that in this case q is the magnitude of the charge on both cylinders – not their sum

Lab I
Measurements of the Electrical Potential Field

Purpose:
The purpose of this lab is to analyze the electric field distribution between two charged conductors. This will be accomplished by determining the position of the equipotential lines between two conductors with the aid of a multi-meter and DC power supply. Using the orientation of the equipotential lines, the vector electric field can be determined in the region between the two conducting bodies.

Materials (for both days):

- DC Power Supply
- Multimeter
- Conducting Paper (3 sheets)
- Two straight conducting bars
- Two conducting disks
- One large conducting ring
- Ballpoint gel pen
- Rubberized Platform with resistor circuit

Procedure:

Day 1
1. Place conducting sheet on rubberized plat form, lining up the holes.
2. Place conducting bars on the conducting paper with <u>ridge</u> side down and facing inward, affix with provided thumb screws (see fig. 1). Be sure that the paper is flush with the rubberized platform.
3. Attach the positive (red) power supply lead to the right conducting body, and the negative (black) lead to the left (see fig. 1). Adjust the power supply to 8V.
4. Set the multimeter to 20V scale. Touch the negative lead of the multimeter (from the "Com" port) to the left bar and the positive (from the "V" port) to the right. Verify that the potential difference between conducting plates is 8.00±0.02V otherwise adjust the power supply using the voltage knob accordingly.
5. Insert the negative lead of the multimeter into the first port (from the left) between the resistors. Using the positive probe tip, locate and mark at least six points on the conducting paper where the multimeter reads 0V. Be sure that you are not touching either the electrodes or the conducting paper when you do this.
6. Move the negative lead of the multimeter to next port on the platform and repeat step 5, do this for each of the ports on the platform.
7. The dots indicate the equipotential lines at 1V increments. Draw the equipotential lines using the dots from your measurements. Upon completion you should have seven clear equipotential lines.
8. Make sure your lab station is cleaned and organized before you leave.

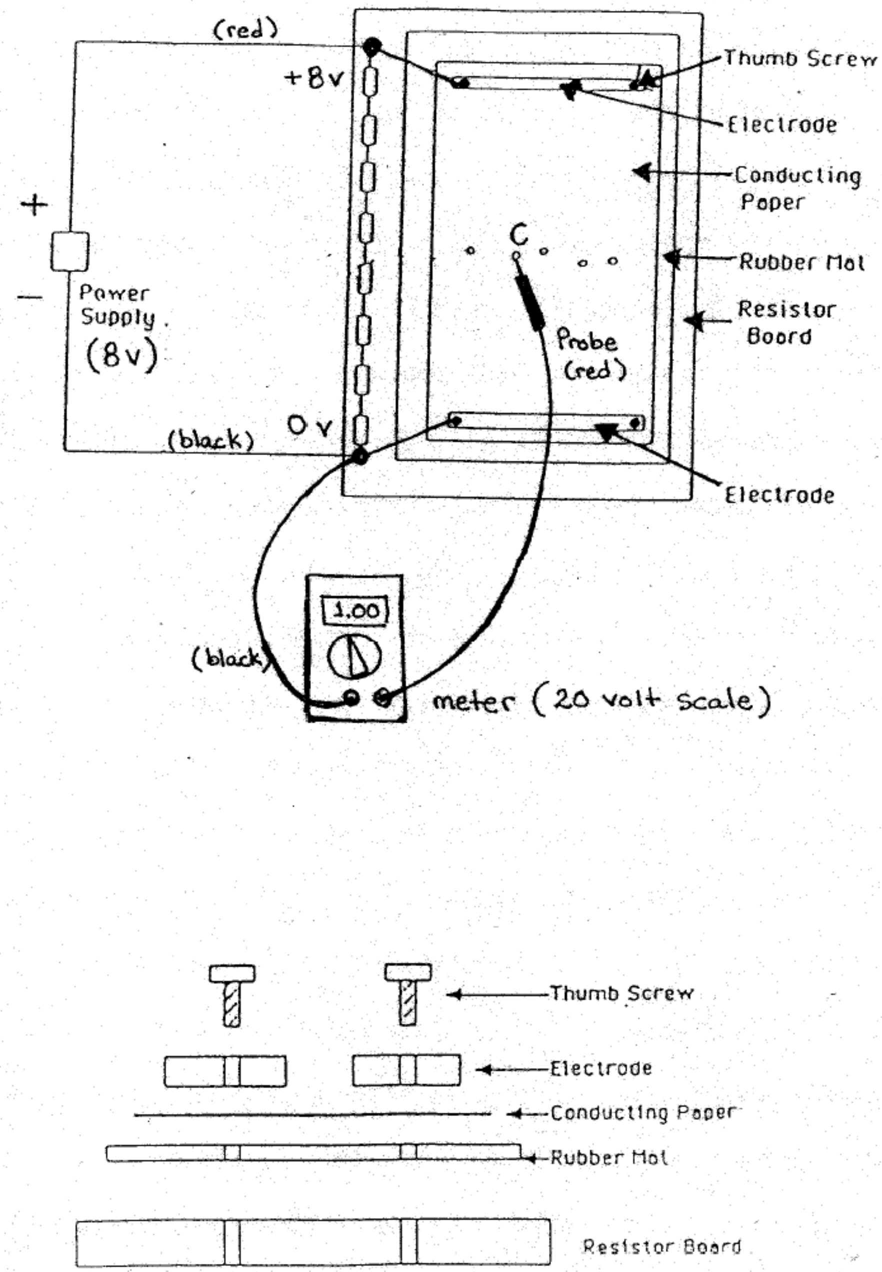


Figure 1

Day 2

1. Set up the platform as it was done on day one except using the two conducting disks instead of the straight bars, this will simulate an electric dipole (see fig. 2).

2. Repeat the procedure used on day one to determine the equipotential lines. Note that the lines will be curved, more than six points maybe necessary to get a clear representation of the lines.
3. Set up the platform with a new sheet of conducting paper. Affix the conducting disk in the center of the platform and the larger ring surrounding the disk (see fig. 3).
4. Repeat the measurement of the equipotential lines as done previously.

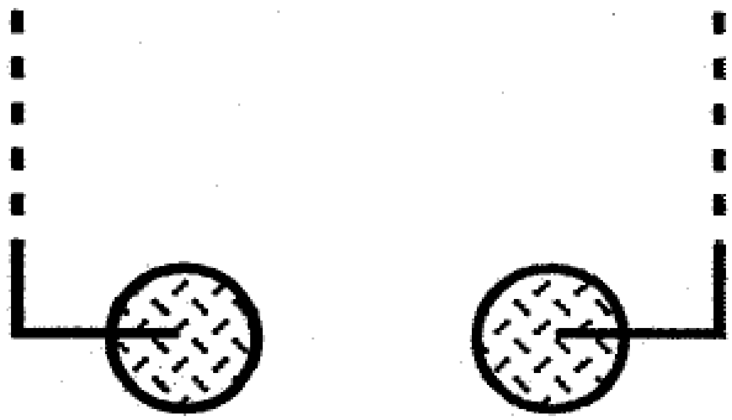


Figure 2

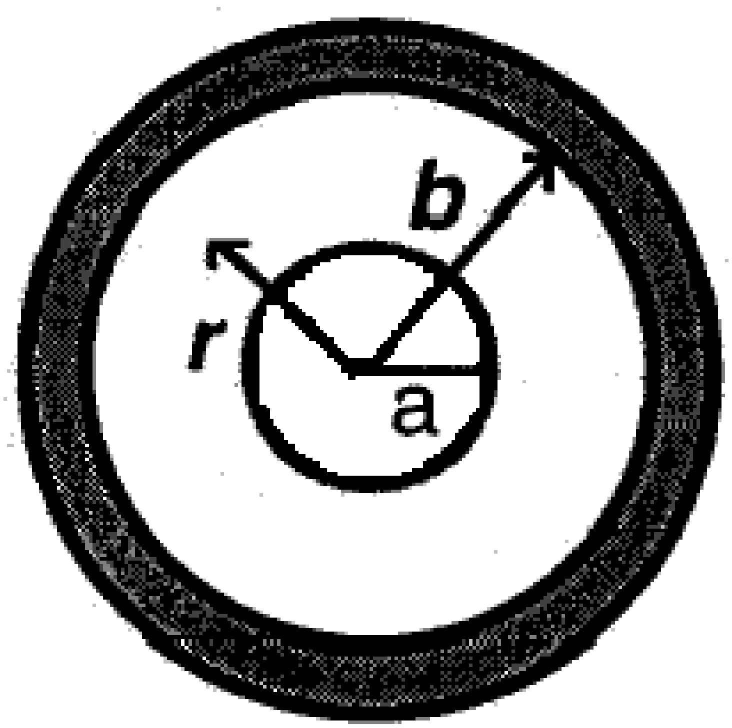


Figure 3

Results

- Parallel Plates and Dipole Configurations

Measure the distance between each equipotential line and enter the value in the table under Δr. Find the magnitude of the electric field by using the equation $|E| = \Delta V/\Delta r$, note that $\Delta V=1.0V$ for each step. For the dipole configuration, measure along the axis created by the line through the centers of the two disks. For the measurement of Δr, orient the ruler such that it is as close to perpendicular with both the equipotential lines as possible.

- Coaxial Configuration

Determine the magnitude of the electric field in the same manner as above ($|E| = \Delta V/\Delta r$). The point where the electric field magnitude is this value is halfway between the two equipotential lines on the axis of measurement, also record the distance of the point from the center of the inner disk (r). Using the equations:

$$V(r) = V_0 - V_0 \frac{[\ln(r/a)]}{[\ln(b/a)]}$$

$$|\mathbf{E}(r)| = |\partial V/\partial r| = \frac{V_0}{[\ln(b/a)]}\frac{1}{r}$$

where V_0=8V, a is the radius of the inner disk, b is the distance from the center to the inner edge of the outer ring, and r is the distance from the center to the point in question (see fig. 3), calculate a theoretical value at each measured point. Make graphs of V vs. r and |E| vs. r, with a smooth curve representing the theoretical equations and dots representing the experimental data. These graphs should be clearly labeled and titled.

- Electric Field Lines

Make a carbon copy of the conducting paper for each configuration so that each group member has a diagram of the configuration with the experimentally determined equipotential lines drawn in. Sketch the electric field lines for each configuration; remember that the field lines are perpendicular to the equipotential lines and are directed from higher to lower potential.

- Turn in a completed data sheet along with the graphs and a cover sheet for each group member.

Data Sheet

- Parallel Plates

Δr (m)	|E| (V/m)

- Dipole

Δr (m)	|E| (V/m)

- Coaxial

Experimental Data

r (m, from center)	Δr (m)	|E| (V/m)

Theoretical Data

r (m, from center)	V (V)	|E| (V/m)

- Conceptual Questions
    1. If an electron was placed within the electric field of each configuration, in which direction would it initially move?

    2. Did the experimental data match well with the theoretical expectations for the coaxial configuration? What were some sources of error in the experiment?

    3. Was the electric field constant for any of the configurations? Why?

Appendix B

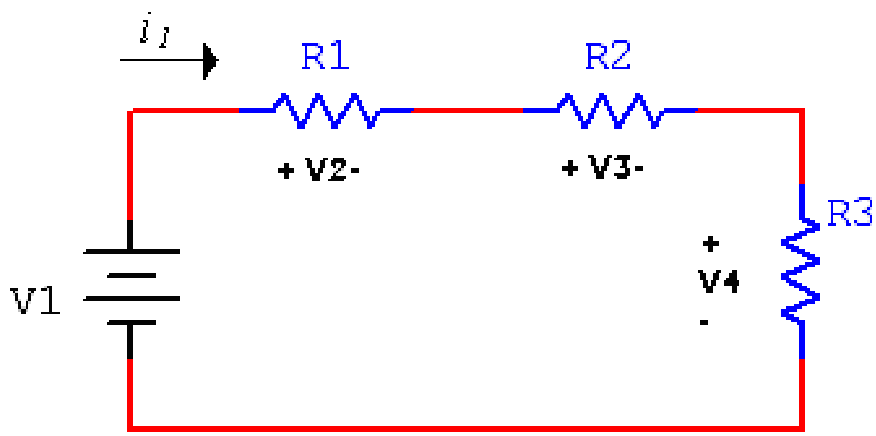
Circuit Experiment

- Pre-lab Problem Set
- Pre-lab Solution Guide
- New Instructions

Light Bulb and Resistor Circuit

Pre lab 2

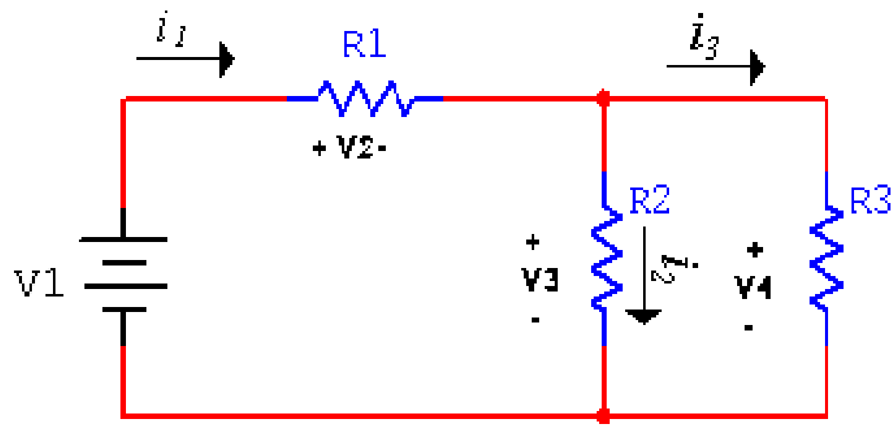
1.



a. **Calculate : i_1, V_2, V_3, V_4, if V_1=12V, $R_1 = R_2 = R_3 = 4k\Omega$**

b. **Calculate : i_1, V_2, V_2, V_4, if V_1=12V, $R_1 = 1\ k\Omega$ $R_2 = 2\ k\Omega$ $R_3 = 3k\Omega$**

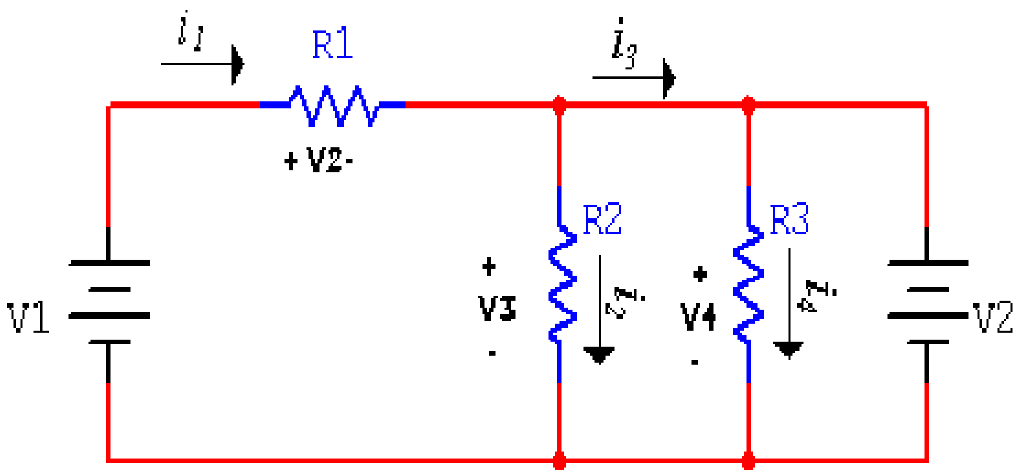
2.



a. **Calculate :** i_1, i_2, i_3, V_2, V_3, V_4, **if** V_1**=12V,** $R_1 = R_2 = R_3 = 6k\Omega$

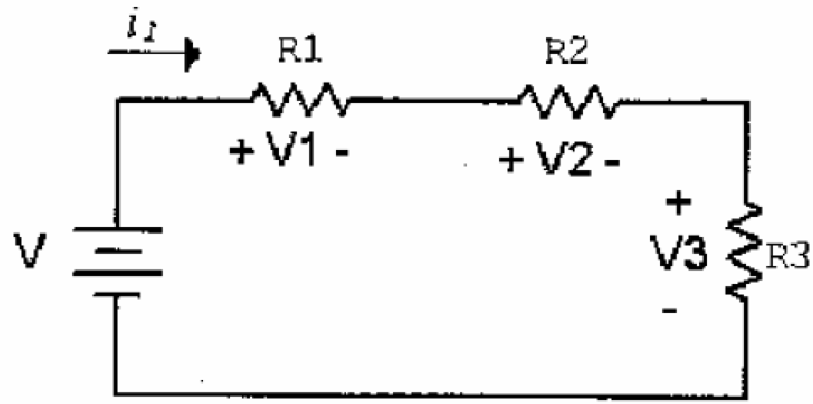
b. **Calculate :** i_1, i_2, i_3, V_2, V_2, V_4, **if** V_1**=12V,** $R_1 = 6\ k\Omega$, $R_2 = 12k\Omega$
$R_3 = 12\ k\Omega$

3.



Calculate : i_1, i_2, i_3, i_3, V_2, V_2, V_4, if V_1=12V, V_2=6V, R_1 = 6 kΩ, R_2 = 6kΩ , R_3 = 6 kΩ

Solution



1.

a

$$V = i_1 R_{eq}, \quad R_{eq} = 4k\Omega + 4k\Omega + 4k\Omega = 12k\Omega$$

$$i_1 = \frac{12V}{12k\Omega} = 1mA$$

$$V_1 = i_1 R_1 = 1mA(4k\Omega) = 4V$$

$$V_2 = i_1 R_2 = 1mA(4k\Omega) = 4V$$

$$V_3 = i_1 R_3 = 1mA(4k\Omega) = 4V$$

b

$$V = i_1 R_{eq}, \quad R_{eq} = 1k\Omega + 2k\Omega + 3k\Omega = 6k\Omega$$

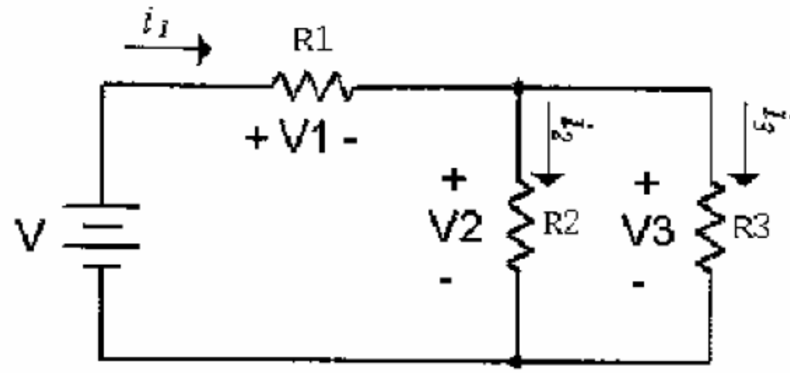
$$i_1 = \frac{12V}{6k\Omega} = 2mA$$

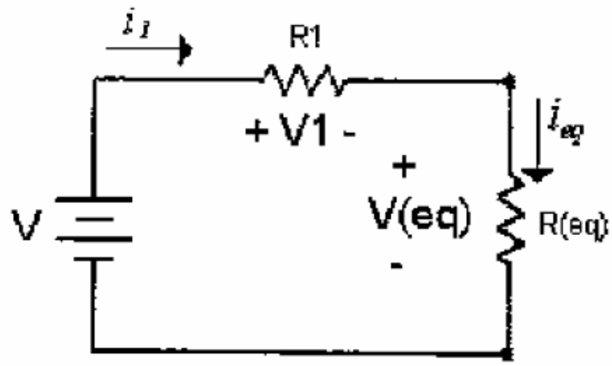
$$V_1 = i_1 R_1 = 2mA(1k\Omega) = 2V$$

$$V_2 = i_1 R_2 = 2mA(2k\Omega) = 4V$$

$$V_3 = i_1 R_3 = 2mA(3k\Omega) = 6V$$

2.





a.

$$V = i_1(R_{eq} + R_1), \quad R_{eq} = \frac{1}{\left(\frac{1}{6k} + \frac{1}{6k}\right)} = 3k\Omega$$

$$i_1 = \frac{12V}{6k + 3k} = \frac{4}{3}mA$$

$$V_1 = i_1 R_1 = \frac{4}{3}mA(6k\Omega) = 8V$$

$$V_{eq} = i_1 R_{eq} = \frac{4}{3}mA(3k\Omega) = 4V$$

$$V_2 = i_2 R_2 \quad V_2 = V_{eq}$$

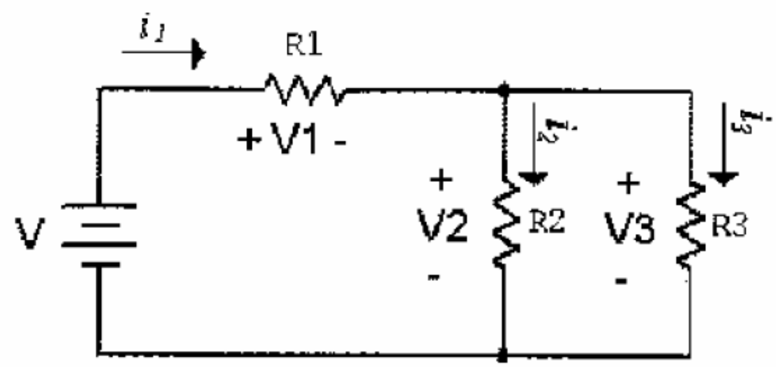
$$i_2 = \frac{4V}{6k} = \frac{2}{3}mA$$

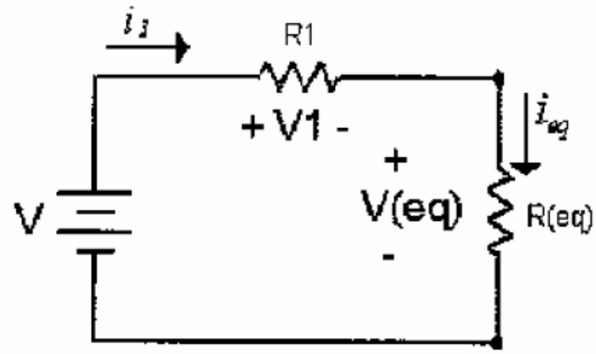
$$V_2 = V_3 \quad becase R_2 \,//\, R_3$$

$$V_3 = 4V$$

$$i_2 = i_3 \quad becase R_2 = R_3$$

$$i_3 = \frac{2}{3}mA$$





b.

$$V = i_1(R_{eq} + R_1), \quad R_{eq} = \frac{1}{\left(\frac{1}{6k} + \frac{1}{12k}\right)} = 4k\Omega$$

$$i_1 = \frac{12V}{6k + 4k} = 1.2mA$$

$$V_1 = i_1 R_1 = 1.2mA(6k\Omega) = 7.2V$$

$$V_{eq} = i_1 R_{eq} = 1.2mA(4k\Omega) = 4.8V$$

$$V_2 = i_2 R_2 \quad V_2 = V_{eq} = 4.8V$$

$$i_{eq} = \frac{4.8V}{4k} = 1.2mA$$

$$V_2 = V_3 \quad becase R_2 \, // \, R_3$$

$$V_3 = 4.8V$$

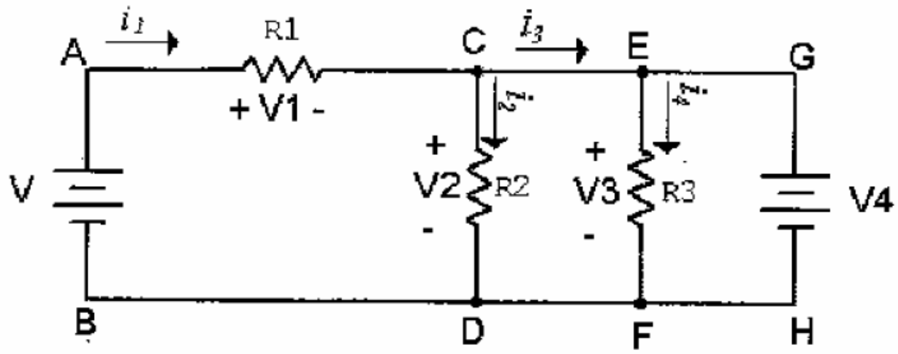
$$V_2 = i_2 R_2$$

$$i_2 = \frac{4.8V}{6k} = .8mA$$

$$V_3 = i_3 R_3$$

$$i_3 = \frac{4.8V}{12k} = .4mA$$

3.



b. Calculate : i_1, i_2, i_3, i_4, V_1, V_2, V_3, if V=12V, R_1 = 2 kΩ R_2 = 3 kΩ R_3 = 4kΩ

Loop AGHB

$12V - 2ki_1 - 6V = 0 \quad (divide\ by\ 1000)$

$12mV - 2i_1 - 6mV = 0$

$2i_1 = 6mV$

$i_1 = 3mA$

Loop ACDB

$12V - 2ki_1 - 3ki_2 = 0 \quad (divide\ by\ 1000)$

$12mV - 2i_1 - 3i_2 = 0 \quad (sub\ i_1 = 3mA)$

$12mV - 6mV = 3i_2$

$3i_2 = 6mV$

$i_2 = 2mA$

Loop AEFB

$12V - 2ki_1 - 4ki_4 = 0 \quad (divide\ by\ 1000)$

$12mV - 2i_1 - 4i_4 = 0 \quad (sub\ i_1 = 3mA)$

$12mV - 6mV = 4i_4$

$4i_4 = 6mV$

$i_4 = 1.5mA$

$i_1 = i_2 + i_3 \quad (sub\ i_1 = 3mA, i_2 = 2mA)$

$i_3 = 1mA$

$V_1 = i_1R_1 = 3mA(2k\Omega) = 6V$

$V_2 = i_2R_2 = 2mA(3k\Omega) = 6V$

$V_3 = i_4R_3 = 1.5mA(4k\Omega) = 6V$

Experiment #2: Part 1

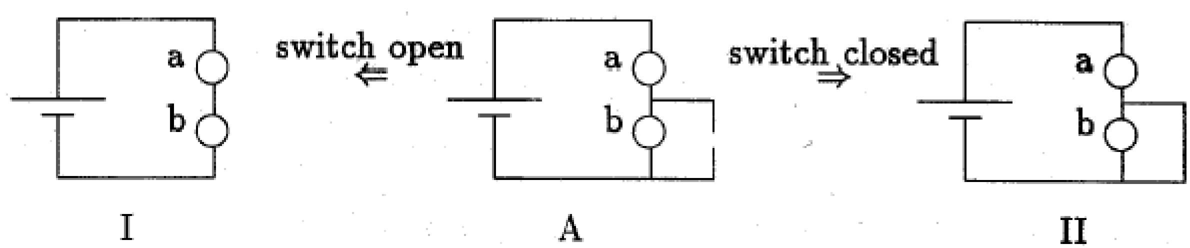
Light Bulb Experiments

1. **Purpose**: To predict current flow in simple resistive circuits.
2. **Model**:

- A light bulb is an example of a resistor.
- The brightness of a light bulb is a measure of the amount of current flowing through it. For identical light bulbs, the brighter the bulb, the greater the current.

3. **Procedure**: Record all of your predictions and observations below. If your predictions were incorrect, explain why.
4. This data sheet will be collected following the completion of Part 2 of the experiment. The instructor will issue a specific due date.

Circuit A: **Resistors in Series.**



1. How do you expect the intensities of the light bulbs *a* and *b* will compare with one another in Circuit I?

Connect the light bulbs provided as shown to create Circuit I, and test your prediction (Note that if the bulbs are not quite identical, there might be minor differences; these should be ignored).

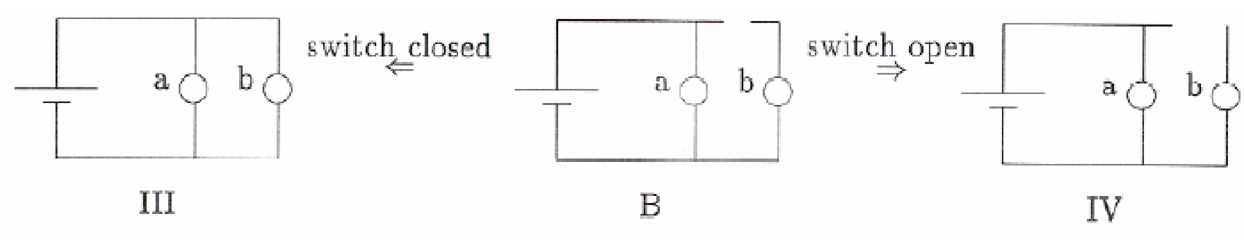
2. Predict how the intensities of light bulbs *a* and *b* will compare to each other when the switch is closed (changing Circuit I into Circuit II)? How will they compare to the ones in Circuit I (when the switch was open)?

Modify the circuit and observe whether your prediction is correct.

3. What can you deduce about the currents through two resistors in series?

4. What happens if one reverses the direction of the battery in the Circuit I?

Circuit B: Resistors in Parallel.



5. How do you expect the intensities of the light bulbs *a* and *b* will compare with one another in Circuit III?

Connect the light bulbs provided to create Circuit III, and test your prediction.

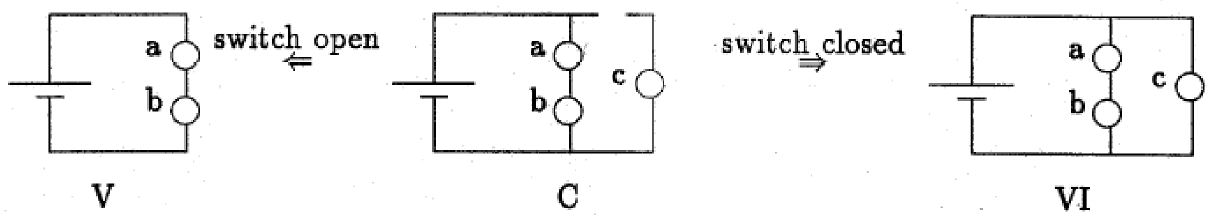
6. How do you expect the intensities of light bulbs *a* and *b* will compare to each other when the switch is open (changing Circuit III into Circuit IV)?

Modify your circuit and observe whether your prediction were correct.

7. What can you say about the current flowing through the battery in Circuits III and IV?

8. How does the intensity of light bulb *a* vary from Circuit III to Circuit IV? Why?

Circuit C:



9. How do you expect the intensities of the light bulbs *a* and *b* will compare with one another in Circuit V?

Modify your circuit and observe whether your prediction were correct

10. How do you expect the intensities of light bulbs *a* and *b* will compare to each other when the switch is closed (changing Circuit V into Circuit VI)? How do you expect the intensities of bulbs *a* and *c* will compare? How do you expect the intensities of bulbs *b* and *c* will compare?

Modify the circuit and observe whether your predictions are correct.

11. How does the intensity of light bulb *a* vary from Circuit V to Circuit VI? Why?

Experiment #2: Part 2

Light Bulb Experiments

1. **Purpose.** To analyze a two-loop circuit containing resistors and batteries, construct the circuit and compare theoretical results with measurements of voltages and currents made on the circuit.

2. **Required equipment.** Equipment for this experiment is listed below:

Quantity	Description
1	Resistor: 100 Ω (R_1)
1	Resistor: 220 Ω (R_2)
1	Resistor: 330 Ω (R_3)
2	"D" Cell battery
1	battery holder
	copper springs
1	multimeter

3. **Prediction.** We will investigate a multiloop circuit. A circuit diagram is shown in Fig. 1. You must compute the expected current through and voltage drop across each resistor. The batteries will be separated and can be placed in each position in either direction. For your calculations, use the value $\mathcal{E} = 1.57\,\mathrm{V}$ for each battery; the internal resistance of the batteries can be neglected. Place your results in a table with two blank columns for experimental values to be inserted in part 5.

4. **Resistor color code.** The resistance value of a resistor is coded by colored rings on the body of the resistor. A numeric digit is associated with each color. This association is shown in the following table:

black	0	green	5
brown	1	blue	6
red	2	violet	7
orange	3	gray	8
yellow	4	white	9

Starting with the rings closest to one end, the first two rings give a two digit value and the third ring, the power of ten. As an example, consider a resistor with the rings <yellow,violet,red>. The resistance value is $47 \times 10^2\ \Omega$ or $4.7\ \mathrm{k}\Omega$.

We have considered only the first three rings but there may be more than three rings on a resistor. The other rings have different meanings, for example, the acceptable error or tolerance in the resistance value. The resistors used in this experiment have a tolerance of 5%.

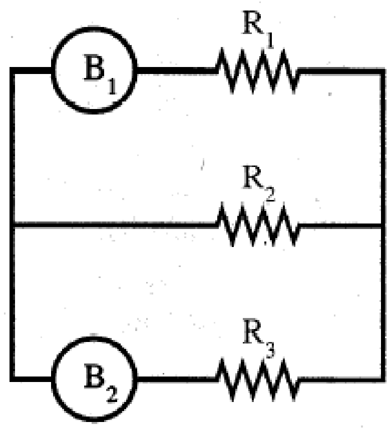


Figure 1: Loop circuit.

5. **Procedure.** Construct the circuit shown in Fig. 1. Use the springs to connect the resistor leads together by pushing the lead into the side of the spring with the lead perpendicular to the axis of the spring. For this circuit, the two batteries are used independently, and they may be oriented in either direction. Be sure to record the battery directions in an accurate circuit diagram. Carefully measure the potential across each resistor with the multimeter and write the values in your table; be sure your multimeter is set to "Volts". You should get agreement with your theoretical calculation to within 5%. If you do not get agreement, check your theoretical calculations and the construction of your circuit, then ask the instructor for help.

   Measure the current through each resistor by setting the multimeter to "Amps" and placing it in series with the resistor. Note that you may have to break the circuit in order to insert the multimeter. Again, you should get agreement with your theoretical calculation. Record all your measured values in your table.

   Also calculate the power dissipated by the resistors and supplied by the batteries.

6. **Cleaning up.** At the end of the lab period, disassemble your circuits and place all resistors and springs in the plastic bag in which they were supplied. Remove the batteries from the holder and place them in the storage box supplied by the instructor.

7. **Data.** Record all measured and calculated values in the Data Table below.

$$V = IR, \quad P = I^2R,$$

$$\text{Error} = \{|(\text{calculated}) - (\text{measured})| / (\text{calculated}) * 100\}\ \%$$

Data Table	**Resistor 1** Resistance: Ω	**Resistor 2** Resistance: Ω	**Resistor 3** Resistance: Ω	**Error %**
Measured Current (A)				
Calculated Current (A)				
Measured Voltage (V)				
Calculated Voltage (V)				
Calculated Power (W)				
Measured Power (W)				

Appendix C

Magnetic Field Experiment

- Pre-lab Problem Set
- Pre-lab Solution Guide
- Instructions - First Edition
- Instructions – Revised Edition
- Data Analysis Spreadsheet

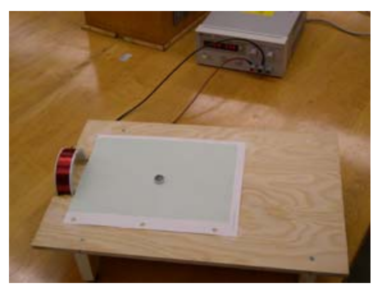
- Magnetic Field Mapping

(Revised Edition)

Purpose: You will measure the ambient magnetic field in the lab room using a compass and a solenoid. You will also get a chance to learn about using Microsoft Excel for data analysis. This experiment includes an error analysis section, where you will consider what factors contribute to the uncertainties in your measurements. You will also get a chance to see how these uncertainties propagate through your calculations and limit the precision of the measurement you are trying to take. Error analysis is an essential part of experimentation. The precision of any quantity you determine experimentally is limited by the precision of the instruments you use to take your measurements when conducting the experiment. It is therefore important to understand what factors can create uncertainty in a measurement, and how uncertainties in measurements translate into uncertainty in results determined using those measurements. For a more complete explanation or error analysis, see ***An Introduction to Error Analysis*** by John Taylor.

Overall this experiment should help to improve your understanding of magnetic fields, and will you give you a good introduction to the rigors of experimentation and error analysis.

Apparatus:



- small platform with a solenoid affixed to one side
- power supply
- small compass
- sheet of mm graph paper

Theory: The magnetic field at a point in space is the vector sum of the magnetic fields produced by all sources. The goal of this experiment is to use a magnetic field whose magnitude and direction can be theoretically predicted to measure the ambient magnetic field in the lab room with uncertainty. The majority of this ambient field is due to the Earth's magnetic field, but there may be other contributions due to current flowing elsewhere in the room, or even natural magnets in the vicinity. The magnetic needle of a compass aligns itself with the ambient magnetic field, and thus its direction represents the direction of the net field at that location.

Procedure:

- Measure the inner radius, outer radius, and thickness of the solenoid. Each quantity should be accompanied by an uncertainty determined by the precision of the instrument you used to take the measurement.
- Carefully cut off one of the short sides of your graph paper, so that the grid lines begin at the very edge of the paper
- Place your graph paper on the platform so that the cut side is flush with the solenoid and the center line on the paper is aligned with the center axis of the solenoid. Once it is well aligned, tape the graph paper down at all four corners, then mark the solenoid axis on the paper.
- Place the compass on the graph paper so that north points along the lines perpendicular to solenoid's axis and rotate the entire platform until the compass needle points north. Once you have the platform aligned, the magnetic field produced by the solenoid will be perpendicular to the ambient field, which will make all of the calculations you have to perform much simpler.
- Connect the solenoid to the power supply, and adjust the current to between 0.2 and 0.5 Amperes. Current sources like the ones you are using can be extremely dangerous. **Any group that raises the current above 0.5 Amperes will receive an automatic zero for this lab.**
- Place the compass on the solenoid axis, centered 1 cm away from the solenoid, and mark the position of both ends of the needle on your graph paper. Repeat this process 24 times, moving the compass 1 cm farther away from the solenoid each time.
- Keep the sheet of graph paper and make copies for your lab partners. You will each need one for your lab report.

Data Analysis:

- You will need a quick introduction to the common notation for uncertain quantities. For an uncertain quantity A, we denote the "best" value as A, and the uncertainty in A as δA. Thus the actual value of A falls somewhere within the range $A - \delta A$ and $A + \delta A$. We write the uncertain quantity as $A \pm \delta A$.
- Now you need to find the angle theta (θ) between the compass needle and the cylindrical axis of the solenoid. Draw an extended line between the two points you marked for the needle direction at each centimeter. Draw the line with a ruler so that its endpoints fall on perpendicular cm lines on the graph paper. The line is the hypotenuse of a right triangle. Measure the lengths of the legs of that triangle by counting up the squares on the graph paper, and determine the angle between the compass needle and the solenoid axis using trigonometry. It is important that you calculate the angle θ as shown in the figure which accompanies these instructions. The formulas in the Excel spreadsheet you will be using to analyze your data assume that θ is measured exactly as shown in the figures below. Excel also assumes that all angles are given in radians, so keep this in mind when calculating the angles. Lastly, you should estimate an uncertainty in θ, $\delta\theta$, based on how well you think you were able to measure the direction of the compass needle.
- Use the equation which you have derived for magnitude of the magnetic field ($B_S(z)$) a distance z along the central axis of a solenoid to calculate the magnitude of field due to the solenoid at each point where you took an angle measurement with your compass The Excel spreadsheet which accompanies this lab, will do the bulk of these calculations for you. The value for x in the spreadsheet is the distance measured from the cut edge of the graph paper. The spreadsheet determines z by adding 1/3 of the thickness of the solenoid to your x value. This is a fairly good approximation for the aggregate field due to every individual loop in the solenoid, despite the fact that they are not truly in the same plane, which is assumed in the equation for B_S. For the radius of the solenoid, you should use the average of the inner and outer radii you measured. These adjustments will also be made for you by the

Excel spreadsheet that accompanies your lab instructions.

- Create a graph of the B_S vs $\cot(\theta)$ on a separate sheet of millimeter graph paper. There are a few unique features of this graph that you should be aware of. First, because the cotangent function has an asymptote at $\theta = 0$ (and goes to ± infinity), the uncertainties that the excel spreadsheet calculates for θ can be very large when θ is close to zero. The equation used in the Excel sheet for calculating $\delta[\cot(\theta)]$ from $\delta\theta$ is:

$$\delta[\cot(\theta)] = \left(|\cot(\theta) - \cot(\theta + \delta\theta)| + |\cot(\theta) - \cot(\theta - \delta\theta)|\right)/2$$

As you can see, if $(\theta - \delta\theta)$ is close to zero, the uncertainty in $\cot(\theta)$ can become nearly infinite, which makes data points where θ is near zero useless. Because the values you will calculate for B_S range over several orders of magnitude, you should select one order of magnitude(B_S = # x 10^{-4}, B_S = # x 10^{-5}, etc…)and plot only the points where B_S was on that order of magnitude when you create your graph. Choose an order of magnitude that does not include any of the points where θ was near zero (that is, where the compass was close to the solenoid). Plot the respective values you found for B_S and $\cot(\theta)$ at each distance z along the solenoid axis. You should scale your graph appropriately for the order of magnitude you chose, and add error bars to each of your data points. Once you have plotted all of your data points, draw a line of best fit by eye, and measure the slope of the line. The slope of the line is your experimentally determined value for the magnitude of the ambient magnetic field in the Lab Room (B_A). Next, draw two additional lines on your graph which have the most extreme slope (highest and lowest) for which the lines will still fit within the error bars on your data points. The slopes of these lines are $B_{A\text{-low}}$, and $B_{A\text{-high}}$. To clarify this a little, look at the sample graph provided. Your uncertainty in B_A, δB_A, is the average deviation of $B_{A\text{-low}}$ and $B_{A\text{-high}}$:

$$\delta B_A = \left(|B_A - B_{A\text{-low}}| + |B_A - B_{A\text{-high}}| \right) / 2$$

Lab Report:

Your lab report should contain the data sheets (including the Excel sheet you used) which contain all of your measured and calculated results, the graph paper you used to record your angle measurements, and the graph you created of B_S vs $\cot(\theta)$. Answer these questions on a separate piece of paper, preferably word-processed.

<<LAB REPORT QUESTIONS>>

1.) Calculate B_A directly for one of your data points using the angle θ that you measured at that point, and your theoretically predicted value of B_S at that distance z. You don't need to calculate δB_A. Show all your steps.

2.) What would happen to the field due to the solenoid if *R*, *N* or *I* were significantly changed?

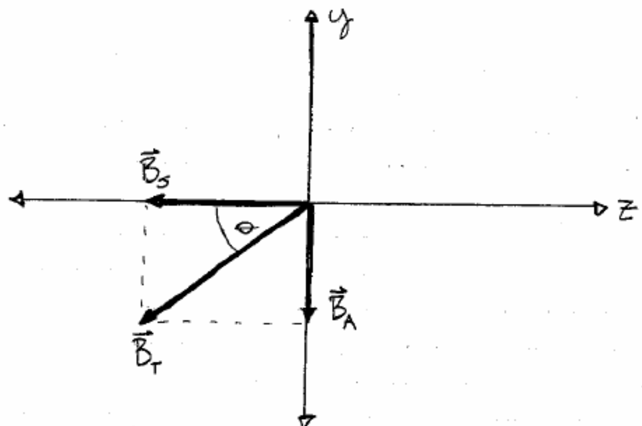
3.) What are the limitations of a real solenoid like the one you used compared to an ideal solenoid?

4.) Comment on your error analysis. Do you think the uncertainties you estimated for your measurements were reasonable? Why or why not? What other factors might have contributed to the errors in your data, and how?

The magnetic field due to a solenoid, along its central axis, is given by

$$\vec{B}(z) = \frac{\mu_0 I N}{2}\left[\frac{R^2}{(R^2+z^2)^{3/2}}\right]\hat{z}$$

R = Radius of Solenoid
N = Number of turns in the solenoid
I = Current flowing in solenoid
z = distance along axis from the center of the loop.



The compass needle points in the direction of B_T, and we have aligned the apparatus so that $\vec{B}_s$ is perpendicular to $\vec{B}_A$

thus $\vec{B}_T = \vec{B}_S + \vec{B}_A = -B_S\hat{z} - B_A\hat{y}$

This makes calculating the angle θ quite simple.

$\tan\theta = \frac{B_A}{B_S}$, which can be rewritten as

$$\boxed{B_s = B_A \cot\theta}$$

$B_S = B_A \cot\theta$ shows a linear relationship between B_S and $\cot\theta$ of the form

$y = mx$, thus by graphing B_S vs $\cot\theta$ you will create a linear graph whose slope is B_A. Follow the methodology shown on the "How to Use Error Bars" to find B_A and δB_A

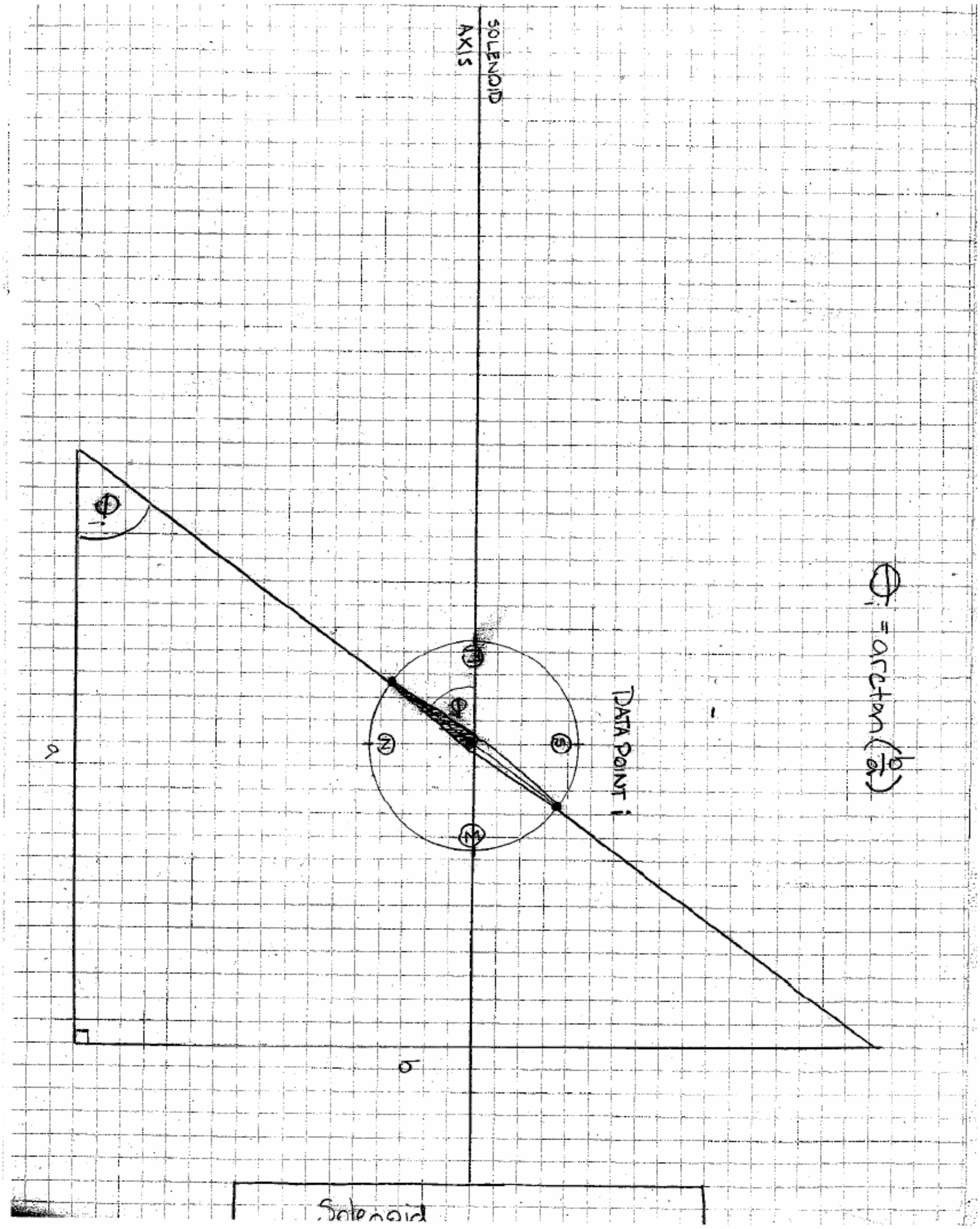
This is a quick mathematical explanation of how the Excel sheet you have been provided determines uncertainties in calculated quantities.

$B(R, N, I, z)$, where $R, N, I,$ & z have uncertainties

$$\delta B_R = \left(\left|B(R+\delta R, N, I, z) - B(R, N, I, z)\right| + \left|B(R-\delta R, N, I, z) - B(R, N, I, z)\right|\right)/2$$

$$\delta B = \sqrt{\delta B_R^2 + \delta B_N^2 + \delta B_I^2 + \delta B_z^2}$$

, δB_N, δB_I, & δB_z are determined in the same fashion as δB_R



SOLENOID AXIS
DATA POINT i
$\Phi_i = \arctan\left(\frac{b}{a}\right)$
Φ_i
a
b
Solenoid

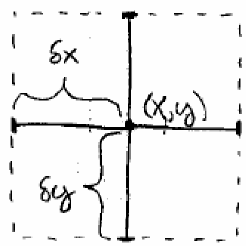
How to use Error Bars

Example Graph

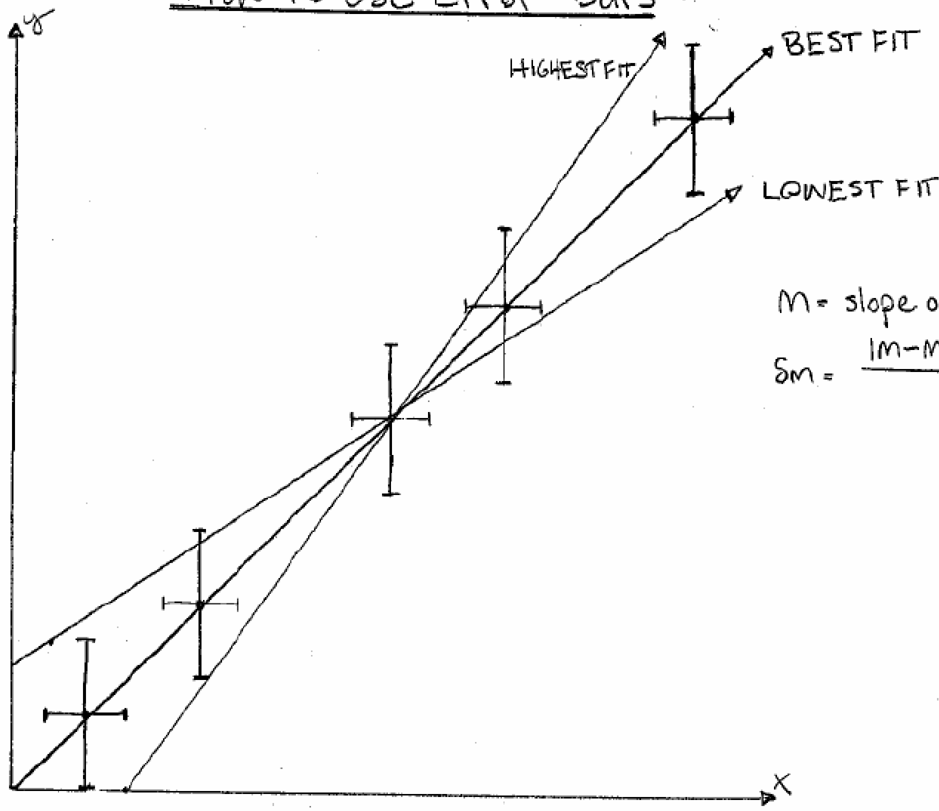
We'll start with a sample data point:

$(x \pm \delta x,\ y \pm \delta y)$

this data point should appear on your graph as shown.



which indicates that the actual values of x & y for the point lay somewhere within the dotted rectangle



m = slope of Best Fit line

$$\delta m = \frac{|m - m_H| + |m - m_L|}{2}$$

In this case, the line of Best Fit is quite obvious, however it may not be so obvious with your data. The lines of lowest and highest fit should be drawn with the most extreme high and low slopes possible, such that the lines still fall within the uncertainty for ALL of your data points. If one or two points seem largely out of place, and will not fit to one of these lines, you may simply exclude it. In this case, you should comment on why you think the point was so far off.

Magnetic Field Mapping
(First Edition)

Purpose: You will measure the ambient field in the lab room using a compass and a solenoid. You will also get a chance to learn about using Microsoft Excel for data analysis. We have included an error analysis section, where you will consider the uncertainties in your measurements, and how those uncertainties propagate through your calculations. Overall this experiment should help to improve your understanding of magnetic fields, and will you give you an introduction to the rigors of experimentation.

Apparatus:

- small platform with a solenoid affixed to one side
- power supply
- small compass
- sheet of mm graph paper

Theory: The magnetic field at a point in space is the vector sum of the magnetic fields produced by all sources. The goal of this experiment is to use a magnetic field whose magnitude and direction can be theoretically predicted to measure the ambient magnetic field in the room. The majority of this ambient field is due to the Earth's magnetic field, but there may be other contributions due to current flowing elsewhere in the room, or even natural magnets in the vicinity. The magnetic needle of a compass aligns itself with the ambient magnetic field, and thus its direction represents the direction of the net field at that location.

Procedure:

- Measure the inner radius, outer radius, and thickness of the solenoid. Each quantity should be accompanied by an uncertainty determined by the precision of the instrument you used to take the measurement.

- Carefully cut off one of the short sides of your graph paper, so that the grid lines begin at the very edge of the paper
- Place your graph paper on the platform so that the cut side is flush with the solenoid and the center line on the paper is aligned with the center axis of the solenoid. Once it is well aligned, tape the graph paper down at all four corners, then mark the solenoid axis on the paper.
- Place the compass on the graph paper so that north points along the lines perpendicular to solenoid's axis and rotate the entire platform until the compass needle points north. Once you have the platform aligned, the magnetic field produced by the solenoid will be perpendicular to the ambient field, which will make all of the calculations you have to perform much simpler.
- Connect the solenoid to the power supply, and adjust the current to between 0.2 and 0.5 Amperes. Current sources like the ones you are using can be extremely dangerous. **Any group that raises the current above 0.5 Amperes will receive an automatic zero for this lab.**
- Place the compass on the solenoid axis, centered 1 cm away from the solenoid, and mark the position of both ends of the needle on your graph paper. Repeat this process 24 times, moving the compass 1 cm farther away from the solenoid each time.
- Keep the sheet of graph paper and make copies for your lab partners. You will each need one for your lab report.

Data Analysis:

- Draw an extended line between the two points you marked for the needle direction at each centimeter. Draw the line with a ruler so that its endpoints fall on perpendicular cm lines on the graph paper. The line is the hypotenuse of a right triangle. Measure the lengths of the legs of that triangle by counting up the squares on the graph paper, and determine the angle between the compass needle and the solenoid axis using trigonometry. It will be most convenient later on if your angles are in radians. Lastly, you should estimate an uncertainty in theta based on how well you think you were able to measure the direction of the compass needle.
- Use the equation which you have derived for the magnetic field a distance z along the central axis of a solenoid to calculate the theoretical field due to the solenoid at each point where you took an angle measurement with your compass (if you use the excel spreadsheet which accompanies this lab, these calculations will be done for you). You should note that z = 0 for the solenoid does not begin at the edge of the graph paper. Set z = 0 about 1/3 the thickness of the solenoid from the edge of the paper. This is a fairly good approximation for the aggregate field due to every individual loop in the solenoid, despite the fact that they are not truly in the same plane. For the radius of the solenoid, you should use the average of the inner and outer radii you measured. These adjustments will be made for you by the Excel spreadsheet that accompanies your lab instructions.
- Create a graph of B_solenoid vs cot(theta) on a separate sheet of graph paper, plotting the respective values at each distance z along the solenoid axis. You should scale your graph

appropriately and add error bars to each of your data points. Once you have plotted all of your data points, draw a line of best fit by eye, and measure the slope of the line. The slope of the line is your experimentally determined value for B_ambient. Next, draw two additional lines on your graph which have the most extreme slope (highest and lowest) for which the lines will still fit within the error bars. The slopes of these lines are B_low, and B_high. To clarify this a little, look at the sample graph provided. Your uncertainty in B_ambient, δB_ambient, is the average deviation of B_low and B_high:

(abs(B_ambient – B_low) + abs(B_ambient – B_high))/2

Lab Report: Your lab report should contain the data sheets (including the Excel sheet you used) which contain all of your measured and calculated results, the graph paper you used to record your angle measurements, and the graph you created of B-solenoid vs. cot(theta). Answer these questions on a separate piece of paper, preferably word-processed.

<<LAB REPORT QUESTIONS>>

1.) What would happen to the field due to the solenoid if R, N or I were significantly changed?

2.) What are the limitations of a real solenoid like the one you used compared to an ideal solenoid?

3.) Comment on your error analysis. Do you think the uncertainties you estimated for your measurements were reasonable? Why or why not? What other factors might have contributed to the errors in your data, and how?

The magnetic field due to a solenoid, along its central axis, is given by

$$\vec{B}(z) = \frac{\mu_0 I N}{2}\left[\frac{R^2}{(R^2+z^2)^{3/2}}\right]\hat{z}$$

R = Radius of Solenoid
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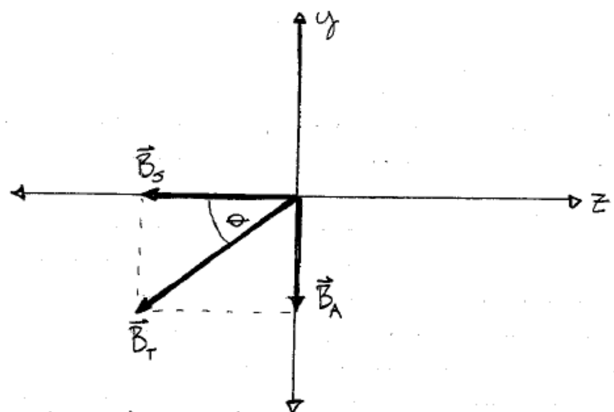

The compass needle points in the direction of B_T, and we have aligned the apparatus so that $\vec{B}_S$ is perpendicular to $\vec{B}_A$

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This makes calculating the angle θ quite simple.

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$B_S = B_A \cot\theta$ shows a linear relationship between B_S and $\cot\theta$ of the form

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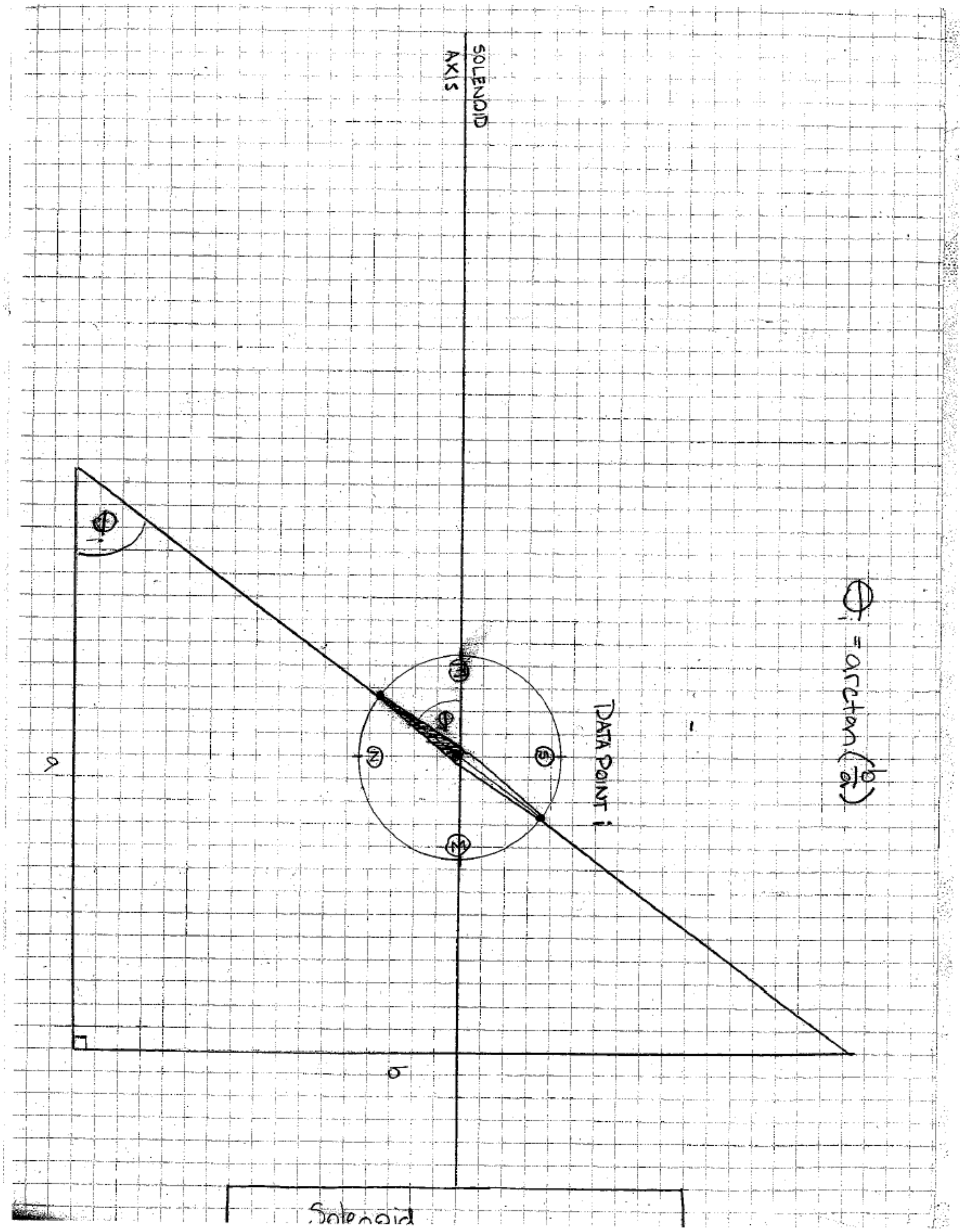
This is a quick mathematical explanation of how the Excel sheet you have been provided determines uncertainties in calculated quantities.

$B(R,N,I,z)$, where $R, N, I, \$ z$ have uncertainties

$$\delta B_R = \Big(\left|B(R+\delta R,N,I,z) - B(R,N,I,z)\right| + \left|B(R-\delta R,N,I,z) - B(R,N,I,z)\right|\Big)/2$$

$$\delta B = \sqrt{\delta B_R^2 + \delta B_N^2 + \delta B_I^2 + \delta B_Z^2}$$, δB_N, δB_I, \$ δB_Z are determined in the same fashion as δB_R


SOLENOID AXIS
DATA POINT 1
$\theta_1 = \arctan\left(\frac{b}{a}\right)$
a
b
Solenoid

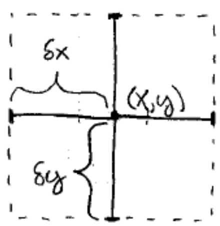
How to use Error Bars

Example Graph

We'll start with a sample data point:

$(x \pm \delta x,\ y \pm \delta y)$

this data point should appear on your graph as shown.



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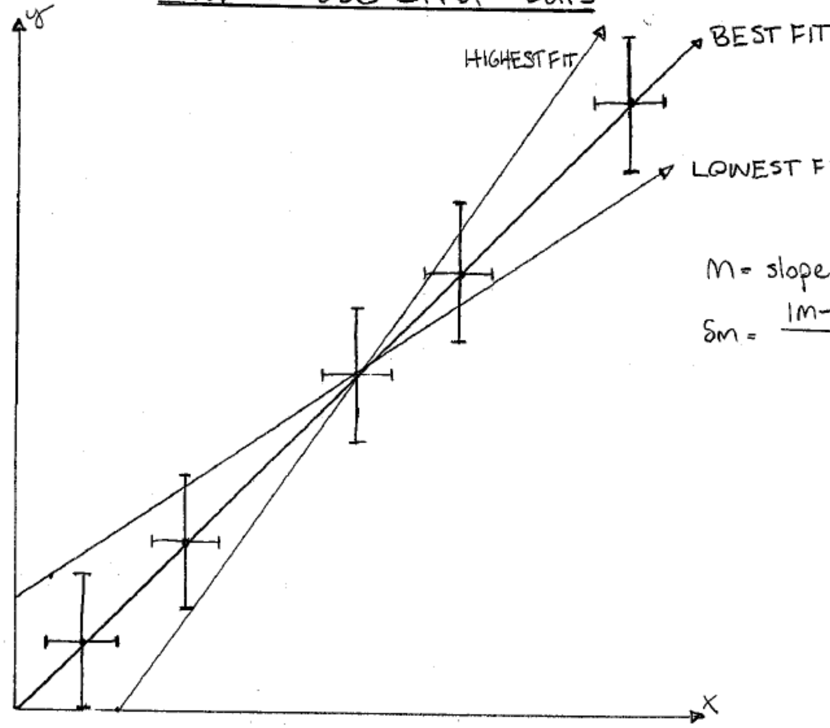

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$$\delta m = \frac{|m - m_H| + |m - m_L|}{2}$$

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Appendix D

Online Student Survey

- Survey Questionnaire
- Student Responses

SURVEY FOR PH 1121 LAB THREE

1. What Physics and Math Courses have you taken (at WPI, at other colleges, advanced hs/AP work)?

Courses:

2. What year are you?

3. What is your major? Or, what choices are deciding upon?

Major:

4. How would you rate your understanding of magnetism--before performing this lab--on a scale of 1-5?

5. How would you rate your understanding of magnetism--after performing this lab--on a scale of 1-5?

6. How valuable do you think this introduction to error analysis has been? <u>Please BE HONEST!!</u>

Error Analysis Comments:

7. In your own words, what do you think the objective of this lab was?

Objective:

8. Is there anything about the lab you would suggest changing, for future courses?

Suggestions:

9. Do you enjoy learning about magnetism, in general? Do you think this experiment covered important material?

Comments:

10. What final letter grade do you expect to receive for PH 1121?

11. Would you wish this experiment on your worst enemy?

S1 year S2 understandingbefore understandingafter S4 S5 S6 S7 finalgrade D3 submit1

Courses:CalculusAB&BC high school at WPI: MA 1024 PH 1110 HI 1031 MA 2051 PH 1121 ES 2001 Freshman Major: Electrical Engineering and Physics 3--Average 3--Average Error Analysis Comments: To be honest, I did not understand the concept behind the lab, I plugged in the numbers to the excel sheet and got the results; I don't know the math behind it or the concepts so I cannot say I learned much. Objective: To learn about error analysis? Suggestions: Maybe give more background info on error analysis and explain the concepts. Comments: I cannot say magnetism is my favorite topic but I don't hate it that much. It's alright once you get the right hand rule and understand how things interact but before that, it's a nightmare!!! Can't tell Yes Submit

Courses: PH1111, PH1121, MA1031, MA1032 AP Calculus AB: 5 AP Physics B: 4 Freshman Major: MA 4--Pretty Good 2--Very little Error Analysis Comments: I think it could have been done better, but I'm perhaps just bitter because my data were awful. Objective: Uh. Suggestions: The experiment would be more practical and conducive to learning, perhaps, if it were easier to implement. The method of drawing lines on graph paper to represent the ends of the compass needle would probably be better if the compass weren't actually larger in diameter than the amount by which it was supposed to be moved in each measurement. A better method might be to mount a compass needle on a pin of some kind (foregoing the compass's casing altogether; the direction of magnetic north could still be measured beforehand using a typical compass). This could greatly increase the efficiency and accuracy with which the dots are drawn on the page (perhaps place a bright lamp directly overheard and trace the needle's shadow). Comments: Magnetism was a fun subject to study. I'm not sure if the experiment is very helpful in understanding the theory behind magnetic fields. A No Submit

Courses: AP Calc (HS), PH1111, PH1121, MA 1023, MA 1024, Basic Statistics and Probability (other college). Freshman Major: Computer Science, Physics 3--Average 4--Pretty Good Error Analysis Comments: I realized that the lab had something to do with error analysis because it was in the spreadsheet, but the lab didn't talk about it too much, or at least not in a way that it had to really be thought about to finish the work. Objective: To understand the properties of a solenoid and how error/error analysis contributes to results and their interpretation. Suggestions: Perhaps increasing the emphasis on error analysis. I realize this may be difficult since the information about solenoids also needs to be emphasized. Comments: I enjoy learning about physics in general, really. Magnetism, as part of physics, is also enjoyable to me. B Yes Submit

Courses: AP Calculus, Calc 3, Calc 4, Physics 1111, Ph 1121 currently Freshman Major:ECE 3--Average 3--Average Error Analysis Comments: Even with some unreasonable degrees of error, the results were rather skewed, so I definitely saw the correlation to appropriate error estimations and reasonable answers.

Objective: Visualize the changes through a magnetic field and understand the degree of uncertainty for more real-life type experiments. Suggestions: Comments: I feel a little more than indifferent on the favorable side toward magnetism. This lab seemed pertinent. B Yes Submit

Courses: MA 1023, PH 1111 Freshman Major: ME 4--Pretty Good 4--Pretty Good Error Analysis Comments: It was very bad, the quality of the instruments was horrible and the experiment was very repetitive Objective:Calculate the ambient filed Suggestions:Materials and not having to force your view to plot 50 points in a graph paper. Comments:I enjoy magnetism, I did not enjoy or learn from the experiment, B Yes Submit

Courses: Physics: AP Physics BC (score: 3), PH1111 Math: AP Calc AB (Score: 4), 2 semesters of Calc at Colby College (Single and Multivariable Calc), MA1024A, MA2051A Freshman Major: ECE major, CS minor, possible ME minor 2--Very little 1--Didn't Learn Anything Error Analysis Comments: I found the lab document to be very poorly organized and lacking in clarity. While I can learn some things about error analysis, I was usually too busy trying to figure out what the instructions were telling me to do to actually learn much from it. Objective: To have us see how error plays a role in experimental measurements and to see how solenoids create magnetic fields. Suggestions: Be much more clear and explicit concerning exactly what the student is to do, and to make sure all measurements are explicitly defined as to what is measured and what the name of the variable is. Also, it would make the instructions much clearer if sections of theory were somewhat separated from sections of instructions. Comments: I find magnetism and electricity interesting in general, though I think this experiment failed because it got bogged down in tedium and time spent trying to figure out what exactly the instructions were referring to. A Yes Submit

Courses: PH1111, PH1121, AP Physics, Physics with Honors AP/IB Calc AB, AP/IB Calc BC, MA1024, MA2051 Freshman Major: Mechanical Engineering 4--Pretty Good 4--Pretty Good Error Analysis Comments: Had I not been taught in highschool, i would have been lost Objective: error analysis Suggestions: better explanations Comments: yes and sortof A No Submit

Courses: PH 1111 AP Calculus (AB) Calculus 3 Freshman Major: Physics 3--Average 3--Average Error Analysis Comments: Valuable, but WAY too labor intensive. The Excel sheet did help, but i couldn't really figure out a good way to find the uncertainty of the angle theta. Objective: To measure the effct of the solenoid's magnetic field on the magnetic field of the room. Suggestions:Less error analysis, I mean come on, that was ridiculous. It took for-frigging-ever. Comments:Magnetism is interesting. Error Analysis is not. It was a cool experiment,illustrating some key concepts. It also illustrated why one should never - under ANY circumstances - analyze error. Given the choice between error analysis and an eighteen foot crocodile, I'd take the eighteen foot crocodile. And I'm deathly afraid of crocodiles. You have no idea. I still can't watch Crocodile Dundee. I like Dundees, but Crocodiles suck. Can't tell Yes Submit

Courses: PH 1111, MA 1023, MA 1024, Double honors physics, Ap physics, Ap calculus AB, Ph 1121 Freshman Major:CS/Aerospace 3--Average 3--Average Error Analysis Comments: Experimental data is never perfect. Understanding the error helps minimizing them. Objective: Learn about magnetic field. Suggestions: NO Comments:Yes A No Submit

Courses: Major: Error Analysis Comments: Objective: Suggestions: Comments: Submit

Courses: AP Calculus AB, Calc3, Calc4, Hon. HS Physics, PH1111 Freshman Major:ECE 3--Average 4--Pretty Good Error Analysis Comments: Not quite sure how the error is calculated...perhaps another revision of the handouts would make it more clear. Objective: 1. Utterly destroy our lives as undergraduate students. 2. Learn about data analysis and the differences between ideal solenoids and a real world situation Suggestions: Specify what X and Z are in terms of the data we got on the sheet which we drew the magnetic field lines Comments: It was worth doing. B Yes Submit

Courses: At WPI: Finished PH 1111 and MA 1024; currently taking PH 1121 and MA 2051. Taken multivariable calculus at UMass - Amherst, and BC calculus in high school. Freshman Major: Physics 2--Very little 2--Very little Error Analysis Comments: It was helpful, and showed that calculating error margins is very important, although my previous lack of understanding of the course material didn't allow me to learn too much about the topic of the lab. Objective: To study the behavior of the magnetic field of a solenoid, and the way erros and imprecision affect measurements in experiments. Suggestions: Not in particular. Comments: Magnetism is a fascinating topic, and it's a lot of fun to learn about it. Even though I haven't kept up with the course very well, I still enjoy reading the material and doing the labs. What was covered in the experiment definitely was important, although I think it might be more applicable in later physics courses, where careful documentation of error sources is essential, than in introductory physics courses, where many experimental values can be estimated to some degree. C Yes Submit