*Preface*

In the summer semester of 2010, I conducted the research below with twelve first year physics students at Kwantlen Polytechnic University as a pilot study to evaluate remote web-based science lab technology using the RWSL being developed at NIC. This research is part of my work towards my M.Ed. in Educational Technology and Learning Design at SFU. The students were able to perform an electricity and magnetism lab from the current Kwantlen Physics 1220 lab manual using the RWSL (from the remote location of Kwantlen in Surrey, BC) without any extra resources from NIC. In fact, I observed students easily learn the controls and collect all of their data in the same timeframe as their traditional hands-on counterparts. It should be also noted that the student lab work produced was indistinguishable from the control group's work to the extent that the lab reports could be blinded from the graders (see the study attached for details). Two graders then used the standard grading rubric from Kwantlen's physics department and found no significant differences in the work produced. A set of learning objectives based on a model for science lab learning objectives (derived from a meta-analysis of the literature) was also investigated and no significant differences in the student experiences with respect to these learning objectives were found. One of the strengths of this study is that the learning objectives used represent the broadest range possible, as opposed to previous research which tends to focus on learning objectives relevant specifically to the technology being evaluated. Furthermore, the students expressed interest about the software used and many commented that they would appreciate using this format in the future to allow them to work at their own pace and at any time. Features that were of interest to the physics staff and faculty who also observed the RWSL were the response time (essentially real time) and the fidelity of the images. I look forward to performing this research on a larger group of students so that results may be generalized to the target population of all post secondary science students. Thanks to Ron Evans, Albert Balbon and Mike Valmorbida for granting me access to the RWSL for my research.

If you have any questions, please do not hesitate to contact me.

Jillian Lang
M.ED. Student at SFU
Contract Instructor-ABE Math and Physics at Kwantlen Polytechnic University
Lab Instructor-Physics at Kwantlen Polytechnic University
604-669-6750
jillian.lang@kwantlen.ca

*Abstract*

The Remote Web-based Science Lab (RWSL) is part of a five-year project to develop a web-based delivery option for the Associate of Science degree program at North Island College. While the theory portion of science courses will easily repurpose to a web-based format, the challenge of offering lab science courses via the web will be the delivery of the lab component. If its quality is insufficient, transfer credit will not be granted consistently. More importantly, the pedagogical value of the labs offered will not result in the desired student learning outcomes. To ensure the high quality of the lab component, a research study was done. This study consisted of an experiment with mixed methods data collection to compare the *performance* of students producing lab work and *experiences* with respect to science lab learning objectives of students randomly assigned into two groups. The control group performed a typical first year level physics lab using the traditional hands-on format and the experimental group performed the same lab using remote web-based technology (the RWSL at North Island College). There were no significant differences between the performance of the two groups with respect to graded lab work. Further, the experiences that students reported were similar with some indications that the experimental group met the learning objectives more than the control group in the areas of professional skills and social skills. There were no important differences between the groups' experiences with respect to conceptual understanding and design skills learning objectives, but it may be of interest that *both* groups responded more positively to the conceptual understanding questions in general and *both* groups responded slightly more negatively with respect to design skills learning objectives. This is more likely due, therefore, to the design of the lab activity itself than the technology used to perform the lab. Since there were only twelve participants, these results cannot be generalized to the target population of all post secondary science students. However, the study provides a model that is scalable to larger sample sizes. The experiment will be repeated with more participants in the future.

## Introduction and Problem Statement

*Introduction*

There is a widely-held belief in the value of experimentation and laboratory work in science education which is supported by theories of instruction including inquiry learning, anchored instruction, and constructivism (Corter, Nickerson, Esche, Chassapis, Im, & Ma, 2007, p. 2). In recent years, a zeitgeist has occurred with the independent worldwide development of remote web-based science lab technology. Students may now log onto the web site of a remotely located science lab and request control of remote instruments through an interface including instrument and camera controls. Data is then collected in real time and real experimental work is conducted at a distance. Although scientists have, for years, been using remotely controlled instrumentation such as telescopes, deep sea submersibles, Mars Exploration Rovers, as well as conducting collaborative project work on remotely located sub-atomic particle accelerators such as TRIUMF, the application of this technology to education is new. Whether remote lab technology can provide students with learning experiences that meet the learning objectives of traditional lab science is controversial and there is very little in the research to settle the debate. This research study provides a model that can be used to evaluate the technology and learn about the ways it is effective.

If remote web-based labs can be shown to an effective tool for the types of things we want students to learn from lab science, there are many advantages over the traditional science lab format: cost savings (needing only one lab setup instead of a class set and reduced setup/takedown technician time); access to labs by more students worldwide including students in remote communities, disabled students and students with care giving responsibilities that are marginalized from regular science work (Scanlon et al., 2004); and remote web-based experiments can be re-run and refined by students, while in the traditional lab, the lab time allotted is necessarily limited. In one study, students reported that “the ability to repeat labs is valued greatly” (Sicker et al., 2005, p. 12). Remote web-based labs may offer flexibility in the timeframe in which the labs can be conducted. In observations of the PEARL project (Cooper, 2005, p. 2), it was found that the remote web-based labs were frequently accessed during the night hours and the students preferred this flexibility. Further, a larger variety of lab experiments (including ones normally too expensive or dangerous) can be offered remotely, another advantage over traditional hands-on labs. For example, experiments in radioactivity or conservation of momentum involving the use of a gun to shoot a bullet into a block of wood would not be practical in a traditional lab, but could be safely explored remotely. In addition to these affordances of remote web-based science labs, there is also an opportunity for a new type of homework: “A reasonable use of sensibly chosen real experiments as remote labs allows a new form of homework and exercises, as well as project work” (Grober et al, 2007, p. 127).

Proponents of remote web-based labs also point out that as time goes on, the line blurs between real and remote lab experiences. More and more instruments are controlled by mouse and keyboard, as the computer replaces instruments such as the oscilloscope, making the operation of equipment remotely or in person more the same than different (Nickerson et al., 2007). An extension of this is the so-called *collaboratory*. Multi-university experiments are becoming more common because of the affordance of remote data collection that networked computers provide, and exposing students to this experience may be of value. Indeed, the trend towards sharing sophisticated instruments on the Internet is growing.

> The Grid2003 Project has deployed a multi-virtual organization, application-driven grid laboratory ("Grid3") that has sustained for several months the production-level services required by physics experiments of the Large Hadron Collider at CERN (ATLAS and CMS), the Sloan Digital Sky Survey project, the gravitational wave search experiment LIGO, the BTeV experiment at Fermilab, as well as applications in molecular structure analysis and genome analysis. (Foster, Kesselman, & Tuecke, 2001, p. 1)

Universities of the future will have the ability to network experiments for their students in a similar way (Wulf, 2003). The possibility of setting up remotely accessible science lab experiments in many different universities that allow students to share access to them all has some unique advantages:

> A worldwide network of clusters of remote labs should be the long-term outcome, offering various experiments. The advantages are obvious: the maintenance of real experiments is not borne by just one institution; everyone can learn from each others' experiences; synergies can be used to solve technical problems; different cultural approaches to install, implement and test a remote lab in learning environments will evolve. (Grober et al., 2007, p. 139)

This shared infrastructure has pedagogical implications. For students who pursue careers in science after graduating, the experience of working in the realistic collaboration with others using shared resources may well be valuable experience. Certainly, the advantages of collaboration in learning has been well established (Pea, 1993).

In the past fifteen years or so, various remote web-based science lab activities (or labs) for students learning science have been developed and documented in science, engineering and education journals. This literature tends to describe these labs and provide rationale for them (Alhalabi, Marcovitz, Hamza, & Hsu, 2000; Aliane, 2006; Bohne, Faltin, & Wagner, 2002; Cooper, 2005; del Alamo et al., 2002; Ertrugrul, 2000; Esche, 2005; Feisel & Rosa, 2005; Forinash & Wisman, 2005; Grober, Vetter, Eckert, & Jodl, 2007; Harms, 2000; Hesselink et al., 2000; Nedic, Machotka, & Nafalski, 2003; Nickerson, Corter, Esche, & Chassapis, 2007; Ogot, Elliott, & Glumac, 2003; Schauer, Ozvoldova, & Lustig, 2008; Sicker, Lookabough, Santos, & Barnes, 2005). Remote web-based science labs typically originate in the area of engineering at larger universities like MIT and Stanford and are often named with an acronym or some other name to identify the lab with the developers. One of the earliest is CyberLab at Stanford (Hesselink et al., 2002). One of the largest is the PEARL project (http://iet.open.ac.uk/PEARL), a major European Union funded project that concluded in 2003 (Cooper, 2005). While these labs vary in many respects, there has been a convergence in the technology used for development and implementation with National Instruments' LabView being the most successful software platform for the computer interface. Appendix A shows a cross section of the remote web-based science labs that have been developed worldwide and the literature describing them.

In a worldwide inventory taken in 2006, Grober et al. (2007) found "about one-third of remote labs dealing with physics and about two-third dealing with engineering techniques […]. Only a few remote experiments were related to other disciplines like chemistry, for example" (p. 129). Recently, a much more versatile remote web-based lab suitable for all science subjects has been developed by North Island College (NIC) ( see http://rwsl.nic.bc.ca/about.html). Since remote web-based science labs are relatively new, many current projects are not yet documented in the literature. Based on the amount of attention paid to the development of remote web-based science labs in recent conferences, we can expect advances in this area to soon appear in the literature, in particular, with applications to biology and chemistry in addition to physics and engineering.

*Problem Statement*

At present, there is widespread development of remote web-based science labs and extensive literature documenting what is being done and providing rationale for it. This development is expensive and is often funded by public funds such as BCcampus and NSF. While there is ongoing debate about the merits of remote web-based science labs in comparison to the other possible types of labs and, at the same time, so much development of them, there is disproportionately little research evaluating their effectiveness. In order to make good pedagogical decisions about the implementation of remote web-based science labs, it is crucial to evaluate their effectiveness. It is also important to learn how students experience them to inform their design and application to optimize their educational value.

## Research Purpose and Questions

*Research Purpose*

The purpose of this research is to compare the performance of two groups of students conducting a typical first year university level physics lab using a traditional hands-on lab format and a remote web-based science lab format to see if there are any differences in effectiveness of the lab formats. The research will also investigate the experiences of the students with respect to science learning objectives to see in what ways, if any, the two formats differ.

*Research Questions*

This research consists of a controlled experiment with mixed methods data collection to answer the following questions:

1) How do first year university level physics students' lab *performance* compare when completing a typical first year university level physics lab in a traditional hands-on lab format to completing the same lab in a remote web-based format?

2) How do first year university level physics students' *experiences* with respect to science lab learning objectives compare when completing a typical first year university level physics lab in a traditional hands-on lab format to completing the same lab in a remote web-based format?

## Research Approach and Rationale

The research consists of a controlled experiment with mixed methods data collection to compare the performance and experiences of twelve first year university level physics students completing a typical first year university level electricity and magnetism lab in a traditional hands-on lab format to those completing the same lab in a remote web-based format. The research presented here is primarily concerned with the evaluation of remote web-based science labs as compared to the traditional hands-on lab format. There are two general ways that student learning as a result of their lab work is evaluated: 1) student *performance* as measured by the grades on their lab reports determined using the standard grading rubric used to evaluate student lab work, and 2) the student *experiences* with respect to science lab learning objectives determined by answers to questions on a questionnaire completed by the students after the lab is completed.

*The Experiment*

An experiment was chosen to allow for a causal relationship to be established, if one exists, between the format used to conduct a lab and the student performance and experiences that result. Participants were randomly assigned to two groups: one group conducted the lab using the remote web-based technology and the other group conducted the lab in the traditional hands-on lab format.

Lab *performance* as measured by the grades on the resulting lab reports of the two groups of students generated quantitative results used to compare performance of students using the remote web-based labs to those conducting traditional hands-on labs.

Student *experiences* were also investigated in terms of a particular set of learning objectives. In reality, learning objectives for science labs vary by subject area among other things. For engineering, the educational goals proposed by the Accreditation Board for Engineering and Technology (ABET, 2005) are the most widely accepted. For physics, the American Association of Physics Teachers' "Goals of the Introductory Physics Laboratory" (AAPT, 1998) are often referred to. And there are others. Problematically, when remote web-based science lab evaluation has been done in the past, it's been done with reference to different sets of educational objectives. It is at least partly because of this that there is no consensus in the evaluation of various remote web-based science labs. The debate about the different modes of delivery of science labs is "confounded by the use of different educational objectives as criteria for judging the laboratories" (Ma and Nickerson, 2006, p. 1).

Ma and Nickerson (2006) conducted an extensive literature review comparing traditional hands-on labs, virtual labs and remote web-based labs. It was found that by selecting, coding and categorizing 60 of the most relevant articles from 1000 articles found on the subject (which were dispersed over 100 different journals and conferences), that there was no standard common criteria used to evaluate the effectiveness of lab work. The articles measure against different objectives, and therefore all seem to be able to claim superiority (p. 7). A four-dimensional model was built by Ma and Nickerson (see Table I) based on the educational goals proposed by the

Accreditation Board for Engineering and Technology (ABET, 2005) and other available taxonomies of lab work by which the articles could be compared (Ma & Nickerson, 2006, p.8).

Table I Learning Objectives of Science Labs

| Lab Objectives | Description | Goals from ABET |
|---|---|---|
| Conceptual Understanding | Extent to which laboratory activities help students understand and solve problems related to key concepts taught in the classroom. | Illustrate concepts and principles |
| Design skills | Extent to which laboratory activities increases student's ability to solve open-ended problems through the design and construction of new artifacts or processes. | Ability to design and investigate<br>Understand the nature of science (scientific mind) |
| Social skills | Extent to which students learn how to productively perform engineering-related activities in groups | Social skills and other productive team behaviors (communication, team interaction and problem solving, leadership) |
| Professional skills | Extent to which students become familiar with the technical skills they will be expected to have when practicing in the profession | Technical/procedural skills<br>Introduce students to the world of scientists and engineers in practice<br>Application of knowledge to practice |

This model was used in this research to design of the questionnaire completed by all of the participants after they performed the lab (see Appendix B). A questionnaire was used so that student experiences with respect to learning objectives could be isolated from each other and any resulting differences could be related to individual objectives. The questions were chosen to address the entire range of learning objectives in this model in an attempt to reveal any important differences between the traditional hands-on and remote web-based labs with respect to these objectives. Closed ended questions were chosen to focus on elements of the learning objectives. This was preferable because the scope and depth of responses could be predicted based on the existing features of the lab topic and the nature of the objectives. Closed ended questions also limited the time required by the students to complete the questionnaire, which was important for obtaining maximum participation as well as being sensitive to the students' time constraints. Since the aspects of lab work that the questions focus on are not naturally ordered, questions with nominal scales were used. The answers resulted in qualitative data appropriate for a comparison of the experiences of the participants with respect to the learning objectives as a result of the different lab formats.

*The Lab Topic*

The e/m (ratio of the charge of an electron to its mass) lab topic was chosen for a variety of reasons. This is a typical fundamental lab that is seen in most first year university level physics courses, so the lab topic is relevant to a very wide audience. The topic of the lab is controlled for between the traditional hands-on and remote web-based lab formats since the same lab is possible for both groups. The e/m lab investigates a fundamental topic in physics, relating electric current in coils of wire (Helmholtz coils) to the voltage applied to electrons (traveling perpendicular to the magnetic field produced by the current in the Helmholtz coils) and the radius of curvature of the resulting path of the electrons. The path of the electrons is a visible beam of blue light that can be seen as a straight line or bent into a circular path produced by the ionization of helium gas in a closed bulb. The apparatus allows for a striking visual representation of the relationship between current, voltage and radius of the beam which is difficult to visualize otherwise. The students make both qualitative observations and quantitative measurements when conducting the lab. The e/m lab involves the entire range of learning objectives outlined in Ma and Nickerson's model: conceptual understanding, design skills, professional skills and social skills (2006, p. 8) and therefore the choice of this particular lab allowed the widest possible range of data to be collected. See Appendix C for the description of the e/m lab used by the participants.

*Rationale*

An experiment with both quantitative and qualitative data was chosen for several reasons. The experiment generated quantitative results based on student *performance* as determined by lab grades that provides evidence regarding how remote web-based labs compare to the traditional hands-on lab format in terms of that outcome measure. Quantitative results are appropriate for the audience of educators in science, accreditation boards and post secondary science departments. Since the research also investigated the *experiences* of the students with respect to lab science learning objectives, qualitative data was collected to allow results to be described thematically. Since it is difficult to gain access to a remote web-based science lab for research purposes, the research is designed to collect as much data as possible to answer all of the research questions while access is granted.

## Methods

Detailed Procedures

*Participants and Context*

The participants for this study are students registered in a first year university level physics class at a BC university in the summer semester of 2010. The students are registered in a single course attended in person for two-hour classes, twice per week. The class limit for the course is 35 students. The physics course content focuses on optics, electricity and magnetism. Students are also required to register for a three-hour lab, once per week. The students are required to register in one of two separate lab sections (since there is a size limitation of 20 students for labs). In the lab, course material is reinforced. Additional areas of learning include measurement, estimation of uncertainty, making decisions about experimental design, measurement, troubleshooting, graphing, analysis of experimental data, drawing conclusions from the results and writing a lab report to communicate what has been learned. There are generally ten such labs per course, done weekly, and they take approximately one to two hours to perform and two to three hours to complete including a lab report. The lab has a lab instructor who is not the course instructor. The lab instructor is responsible for assisting the student with lab work and grading the lab portion of the course which typically counts for 25% of the total course grade. The technician of the host institution of the remote lab is one of the developers of a robotically controlled lab apparatus and interface. He set up the lab equipment and worked with the researcher to facilitate student access to the remote apparatus.

*Sampling*

The participants for the experiment were selected on a voluntary basis from the class. The researcher approached the class at the beginning of the semester and explained the study and handed out a consent form to the class clearly explaining that participation is voluntary and that not participating will not affect their treatment by the lab or class instructors in any way. Participants were made eligible for a prize of $50 which was randomly drawn at the end of the study when the researcher spent time in class explaining the results of the study to the class. The prize was used as an incentive to participate and to compensate participants since completion of the questionnaire is not part of the normal course requirements and was therefore an added task. Consent forms of participants were collected by the class instructor over the next few classes and given to the researcher.

From a list of students who volunteered, a random number table was used by the researcher to randomly assign the participants into two groups, regardless of which lab section they were registered in so that any effect due to lab section was controlled for. One of these groups was randomly assigned to be the control group and no intervention was given to this group (i.e., they completed the lab as they normally would). The other group was assigned to be the experimental group and this group completed the lab via the remote web-based science lab at NIC during the same week that the control group completed the lab.

*The Lab Activity*

The lab conducted by the participants was a typical electricity and magnetism experiment in which the objective is to determine the charge to mass ratio of an electron. The lab is described in the lab manual purchased for the course and this description was used by both groups (see Appendix C). The questionnaire completed by all of the participants was an electronic questionnaire accessed from a link on the course web page. The class instructor informed the participants of its location.

The control group attended the lab in the regular timeslot for that lab. The students were given the option to work alone or in pairs as is always an option for students, given space in the lab.

The experimental group was directed by the class instructor to their course web page which included a link to a schedule in which the students could choose a lab time to complete the lab and a link to the remote web-based lab. The researcher set up the schedule by determining the times when the remote lab could be accessed during the same week that the control group completed the lab. There were certain considerations beyond the researcher's control, such as when a technician was available at the remote site in case problems were encountered. The participants in the experimental group had the option to sign up to work alone or in pairs. The option to work alone or in pairs was therefore the same as it was for the control group. Participants in the experimental group were instructed to come to a room at the university in which a computer had been set up for the remote web-based lab. It should be noted that the intended operation of the remote web-based lab is that it may be accessed from any computer having a standard web browser, but due to some software issues that still exist in the remote web-based lab technology at NIC, it was necessary for the students to come to a computer set up by the researcher for this purpose.

The experimental group's participants logged in to the NIC remote web-based physics lab at the scheduled time and proceeded with the lab. There were some additional controls that are not part of the traditional lab including a camera selection radio button, but their operation was clearly indicated on the interface and the students had no problems navigating these features. All other controls are the same as the lab interface seen in the traditional hands-on lab since the same model of the apparatus, the Nakamura (B10-7350) e/m apparatus, is used in both cases and the interface allows control of the same parameters by mouse. The researcher was present in case students had problems with the remote web-based lab. The researcher is also a lab instructor with experience with the lab, but it was not the intention to provide support in the way a lab instructor does. The researcher was there to simply aid in issues relating to the technology. In two cases, the remote lab server had to be reset and the researcher was required to phone the remote lab to reset the server. Measurements were not lost in this process and the students continued where they had left off.

*Performance Measure*

The independent or treatment variable for the experiment was the lab format that students used for completing the lab. The dependent or outcome variable was the student lab performance as measured by grades on the lab reports determined in the usual way lab reports are graded for this course. The students collected data for the lab and wrote a lab report according to lab report format criteria given at the beginning of the semester. This requires the use of a lab notebook for pre-lab work and for recording raw data in ink, the use of Excel to perform calculations including uncertainty calculations and graphs, and the use of a word processor to write up the lab report.

The lab instructor graded the lab reports according to the standard rubric used for all levels of physics labs at this university (see Appendix D). In order for the research to be as authentic as possible, the same rubric that is normally used in this context was used as opposed to using an external research instrument for grading science lab work (such as SLIC-Student). By using the standard rubric, the validity of the performance measure is ensured to the same degree that lab performance is measured in the normal context of the lab. Another consideration was the intrusiveness of introducing another instrument. It was thought that the addition of another requirement of the students would be unjustifiable given that their workload is already very high for this course. It is also possible that the instrument would introduce an internal threat to validity since student outcomes would now be compared on a less equal basis. For example, students who complete the SLIC-Student may spend less time on the lab work to compensate for the lost time spent on the instrument. It may also be perceived by the student that the instrument is an integral part of the lab and this may have affected their answers on the questionnaire. Although such research instruments may have the advantage of reliability, these advantages do not outweigh the risks.

In addition to the assessment of the lab performance by the lab instructor, the researcher who is also frequently a lab instructor for this course, graded all of the lab reports to increase reliability of the results. The lab grades were marked out of a maximum grade of ten, to nearest ¼ grade as is customary. "Because this method obtains [grades] from two […] individuals, it has the advantage of negating any bias that any one individual might bring to the scoring" (Creswell, 2008, p. 171). A pre-determined benchmark for inter-rater agreement was set at 80 percent, which was to be considered adequate in order to use the average of the lab grades given by the lab instructor and the researcher as the performance measure for each student. If there were inconsistencies beyond this threshold, it was decided that the lab instructor and researcher would review the rubric together and discuss the items in the rubric that allowed the inconsistencies and modify the rubric to ensure better agreement. If this occurred, then all of the lab reports would be re-graded by both the lab instructor and the researcher, and inter-rater agreement checked again, to ensure consistent application of the rubric to all students' work.

For the purposes of assessment, the lab instructor and the researcher were blinded to the group assignment of the students by a process of coding of the lab reports. This was achieved by having the course instructor cover the names on the student lab reports with tape and assigning them numbers (and recording the name-to-number code for later identification). This blinding was possible because the lab was chosen so that lab objective, theory, apparatus, data, results and analysis were identical for both the control and experimental groups and there was no way to distinguish between the lab reports done by the two groups.

*The Questionnaire*

The research included qualitative measures as well as the quantitative performance measure described above. All participants including the participants in the control and the experimental groups were required to complete a questionnaire based on their experiences with respect to questions based on the four-dimensional model proposed by Ma & Nickerson (2006) for lab objectives of science lab work (see Appendix B). The twelve questions on the student questionnaire were designed around these four broad categories: conceptual understanding, design skills, social skills and professional skills, with three questions per category to ensure reliable answers as much as possible. The questions on the questionnaire took the participants approximately ten minutes to complete. The questionnaire was completed after the participants completed the lab and before the graded labs were returned so that the time participants responded was as soon as possible after completing the lab and so that lab grades did not influence student answers.

*Procedure for Establishing Inter-rater Reliability*

As described above, the lab reports were graded by both the lab instructor and the researcher. The inter-rater agreement was calculated as the absolute difference between the grades given by the two graders divided by the total possible grade of 10 (expressed as a percent subtracted from 100). Note that this calculation does not take into account the possibility of agreement due only to chance (as a Cohen's kappa value would), but a high level of agreement is clear from this calculation. It was found that in all cases, the consistency of grades given by the lab instructor and the researcher exceeded the pre-determined benchmark of 80% for this study (see Table II). The average inter-rater agreement was 94.6%.

Table II. Lab Grades (reported as mark out of 10) on the Anonymized Student Lab Reports. Lab report numbers 1-4 belonged to students in one lab section (with one of the lab instructors) and lab reports 5-12 were belonged to students in the second lab section (with a different lab instructor).

| Lab Report Number | Lab Instructor Grade | Researcher Grade | Agreement (%) |
|---|---|---|---|
| 1 | 8 | 8.5 | 95.0 |
| 2 | 8 | 8.5 | 95.0 |
| 3 | 10 | 9.5 | 95.0 |
| 4 | 10 | 9.5 | 95.0 |
| 5 | 7.75 | 8.5 | 92.5 |
| 6 | 7.25 | 8 | 92.5 |
| 7 | 7 | 8 | 90.0 |
| 8 | 7.25 | 8 | 92.5 |
| 9 | 7.75 | 8.5 | 92.5 |
| 10 | 7.75 | 8 | 97.5 |
| 11 | 7.75 | 8 | 97.5 |
| 12 | 7 | 7 | 100.0 |
| Average agreement | | | 94.6 |

## Validity, Generalizability, Reliability and Objectivity

Creswell (2008) defines threats to internal validity as "problems that threaten our ability to draw correct cause-and-effect inferences that arise because of the experimental procedures or the experiences of the participants" (p. 308). Threats to internal validity were minimized in this experiment in several ways.

All of the participants for the study were randomly assigned to the experimental and control groups. The random assignment was used to prevent students from self-selecting into one group or the other and therefore eliminating that bias. Also, the random assignment was done for all participants regardless of which lab section they were registered in. Since there were different lab instructors and days of the week for the two different lab sections, the random assignment eliminated any bias due to things associated with the different lab sections as well. The fact that there were different lab instructors for the two groups is a weakness in the validity of the experiment. Student characteristics might differ slightly as a result of which lab section they were from, introducing a bias into the results. The original design of the experiment controlled for this variable, but due to a logistical change in the remote lab (the original lab planned for was replaced by a different lab from a different course), this was not possible. Future studies will involve experiments in courses having the same lab instructor for the various associated lab sections. This varies randomly by semester due to scheduling constraints.

The conditions for the experimental and control group were closely matched except for the treatment itself to further avoid threats to internal validity. Participants in both the control and experimental groups had the option to work alone or in pairs, which is standard procedure for the labs in this course (and all participants chose to work in pairs). The lab topic and lab description were identical for both groups, using the lab description from their lab manual in both cases (see Appendix C). Both groups had equal access to the manual. Identical models of the lab equipment (i.e., the e/m apparatus and power supplies) were used in the labs conducted by the control and experimental groups. The controls for electric current for the Helmholtz coils and voltage accelerating the electrons had the same ranges and participants had the same options when choosing values for these parameters in both the experimental and control groups. For example, students were required to choose 6-8 values for the accelerating voltage of the electron gun, in approximately equal increments, over the range from 200V to 500V. Similarly current was chosen from any value up to 2A that resulted in the electron beam retaining a constant beam radius. These parameters could be chosen the same way for both groups, using dials on the power supplies. For the control group, dials were physical dials on the front panel of the power supplies and, for the experimental group, dials were displayed on the Labview interface/front panel (adjusted by “grabbing” a picture of the dial and “turning” it with the computer mouse while viewing the resulting changes by way of a camera in real time). The measurement of the diameter of the electron beam was done in the same way by both groups, a visual estimation of the beam diameter on a scale internal to the bulb containing the gas ionized by the electron beam. The control group viewed the bulb directly and the experimental group viewed the bulb through a camera display (with a zoom control). The response to the controls was in real time (with 1/500 second delay in the remote lab, which was not noticeble). The students were able to complete the measurements in the same timeframe as in the control group as witnessed by the researcher who has extensive experience with this lab. It should be noted that there was a “bug” in the remote lab interface which required resetting the camera zoom buttons whenever the camera position was changed. The researcher helped the students with this throughout the experiment (which at times required a phone call to the remote lab to fix), but did not offer any help otherwise.

Threats to internal validity were also avoided by arranging the lab to be completed during the same week of the course for both groups and by limiting the timeframe for the experiment in which confounding variables may develop. The lab was a one-shot situation, so the outcome measure was not likely be threatened by time-dependent factors. Diffusion of treatment is a possible threat to internal validity as the students from each group met class in the time between the treatment and the submission of their lab reports. The researcher required the lab reports to be submitted before the next class to reduce this threat. There may also be some perceived benefit to the treatment group by the participants which may have threatened validity, but the researcher took care to avoid giving this impression when describing the study to the class by emphasizing the similarities between the two.

One important threat to internal validity was that the control group had access to a lab instructor for assistance, while the experimental group did not. This may be an important difference. On the other hand, the lab instructor is generally in the background while students complete lab work in the traditional hands-on lab and students generally work on their own without assistance.

Threats to external validity are “problems that threaten our ability to draw correct inferences from the sample data to other persons, settings, and past and future situations” (Creswell, 2008, p. 310). Ideally, the results from this study would be generalizable to all science labs conducted for any subject in any under graduate post-secondary institution. Because the sample size was small (N-12), results of this study have very limited generalizability.

On the other hand, as a model for future studies with larger sample sizes, this study is designed to avoid threats to external validity. For example, the objectives used on which to base the questions in the questionnaire are based on a model (Ma and Nickerson, 2006) that applies equally well to labs for all science subjects and is not restricted geographically. Also, the experimental design (including the remote web-based technology used) is not subject specific in any way. The lab topic chosen is similar to ones used in the broader population since physics labs are very consistent in post-secondary instruction worldwide and the study can be used as a model to test other lab topics equally well. As well, the questionnaire (with modifications to the specific content referred to in the first three questions), could be applied to any lab. The general lab requirements are standard in post-secondary instruction worldwide as well. Some possibility exists that the technology used here is not the same as would be available elsewhere, but the LabView platform in increasingly used in science labs everywhere, in both traditional hands-on labs and remote web-based labs.

Threats to external validity are also avoided by using the same lab rubric when grading the lab reports that is normally used in grading all physics labs at this university (see Appendix D) and similar to ones used elsewhere. This ensures that the lab grades determined in this study are determined in the same as they would be in the same lab conducted outside the context of this study. Since an entire population of students taking the second semester physics offerings for a semester at this university was solicited in this study, there was no bias introduced by including only certain sections of a course. This increases the ability to generalize to other situations.

Guba (1981) points out that reliability, the requirement that instruments produce stable results, is a necessary precondition for validity (p. 81). Measures were taken to ensure that the results for student performance and student experiences in this study were reliable. High consistency in results was found in terms of the grades assigned to the lab reports given by the lab instructors and the researcher. It was found that in all cases, inter-rater agreement exceeded the pre-determined benchmark of 80%. (Note: all lab reports were also blinded to the graders to ensure objectivity.) Reliability in the questionnaire results was addressed by asking participants three questions per type of lab objective: cognitive skills, design skills, professional skills and social skills and analyzing the answers for each set of three questions (for each student) to ensure that the answers were consistent. Results will be discussed in detail below, but in general, the answers were consistent within each set of three related questions.

It should be noted that many of these questions were included because they are based on the learning objectives in the Ma and Nickerson model (2006) discussed earlier and although this particular lab was chosen to be a good candidate for most of the lab objectives, it did not lend itself equally well to all of the objectives. This experiment, including the choice of questions, is designed so that it could be used with any lab topic and therefore a broad representative selection of questions is represented in the questionnaire. In this way, general learning objectives could be investigated over a series of labs in the future (and not restricted to one lab as in this study) to gain a more realistic representation of what students experience in terms of lab objectives in the full lab component of a semester long course, for example. This explains why some of the questions may appear to be less relevant than others in this study.

## Results and Discussion

### *5.1 Lab Performance*

Descriptive statistics for the grades on lab reports for the control group and the experimental group are shown in Table III, separately by condition. The control condition is the traditional hands-on lab format and the experimental condition is the remote web-based lab format. The lab grades were calculated as the average between the lab instructor's grade and the researcher's grade. The sample size for the experiment was 12 participants in total.

Table III. Lab Grades (reported as mark out of 10) on the Student Lab Reports, by Condition

| | Mean | Std. Dev. | N |
|---|---|---|---|
| Control Condition: Hands-on Format | 8.3 | 1.2 | 6 |
| Experimental Condition: Remote Lab Format | 8.0 | 0.3 | 6 |

Although a t-test comparison would be preferential for generalizing the results to a wider population, the small sample size in this study (N=12) made it more appropriate to do a simple comparison of the means of the grades and their standard deviations. According to the grades on the lab reports, the means for the control and experimental groups were 8.3 with a standard deviation of 1.2 and 8.0 with a standard deviation of 0.3, respectively. At the 95% confidence level, the means (± 2 standard deviations) are 8.3 ± 2.4 (or a range of 5.9 to 10.7) and 8.0 ± 0.6 (or a range of 7.4 to 8.6). The means are contained within the ranges of each other and therefore, there is no significant difference between the mean scores. That is, there is less than 5% chance that there is a difference between the control and experimental groups in the larger population or a 5% chance of a type II error (a false negative).

Since no significant difference was found between the performance of students completing the lab using the traditional hands-on format and the remote web-based format, the null hypothesis is not rejected by this experiment. That is, this study has not shown that there is any difference in performance between the two groups: It could be that there is an effect on student performance as a result of the lab format, but this experiment did not find one. It also may be that no difference exists. Similar studies comparing effectiveness of remote web-based lab format compared to traditional hands-on lab format (Nickerson et al, 2007; Corter et al, 2007; Ogot et al., 2003; Sonnenwald et al., 2003; Scanlon et al., 2004; Sicker et al., 2005) show similar results. It could be that the performance in remote web-based labs is indeed at least equal to that of traditional face-to-face labs as these previous studies suggest and that this study confirms these findings.

Studies with larger sample sizes and more lab topics, over more science subjects would be beneficial in establishing if this conclusion is true of the larger population of all post secondary science students. If it is, then there may be evidence to justify the development of remote web-based lab technology to be used in distributed learning of science to enable students to study science including the lab, while meeting the desired learning goals that this entails. The benefits of this include being able to provide science education at a lower cost since the lab equipment needed for a remote lab is a fraction of what is needed in fully equipped traditional lab. In addition to this, it would enable students who are marginalized from the traditional modes of learning science due to disabilities, care giving responsibilities, remote locations, etc. an opportunity to study science as has been the prerogative of students attending a traditional post secondary institution. And there are many other advantages as described in the introduction of this paper.

Although the means were very close, there was much more spread in the grades in the control group with a standard deviation of 1.2 compared to the standard deviation of 0.30 for the experimental group. Again, this may not be significant since the sample size of this study is so small, but this effect may be looked for in future studies to determine if it exists. It may be that the remote lab format does not allow for as much variation in student performance and this may have implications for student learning.

*5.2 Students' Experiences with respect to Conceptual Understanding Learning Objectives*

The participants' self-reported experiences with respect to science lab learning objectives as a result of performing a typical first year university level physics lab in the traditional hands-on format and the same lab using remote web-based lab technology are described below. As the sample size in this study is only twelve participants, the results of these comparisons cannot be generalized with confidence to the overall population of under graduate science students. The results may, however, suggest areas to investigate in studies with larger sample sizes in the future that could be generalized to the larger population of interest.

The participants in the control group answered "b" ("The lab confirmed what I expected, that […]") to all three of the conceptual understanding questions except in three cases where the answer was given as "a" ("I understood that […] for the first time"). In the experimental group, the results were similar, all answered "b", except four cases of the answer of "a". Since no one answered that they were surprised, unaware or confused by what they observed, it appears that the lab was neutral or slightly effective in affecting student understanding of the concepts in both groups.

Since no apparent differences appeared between groups' experiences with respect to the questions on the conceptual understanding learning objectives, it may be that remote web-based labs offer an equivalent lab experience to traditional hands-on labs. More studies with larger sample sizes and perhaps tests measuring mastery of material as opposed to subjective self reported experiences would be useful in establishing the effectiveness of remote web- based technology with respect to conceptual understanding.

*5.3 Students' Experiences with respect to Design Skills Learning Objectives*

For the question about experiences with respect to problems encountered, the participants in the control group and the experimental group answered "a" ("I was able to create and apply my own solution to at least one problem") approximately the same number of times (3 for control; 2 for remote). The difference between the groups with respect to the remaining answers, namely that the control group had more "d" answers ("I asked the lab instructor or other students for the solution") and the remote group had more "c" answers ("I re-read the manual to figure out the solution") may reflect the fact that the control group had access to a lab instructor to answer questions and the remote group did not. On the other hand, it is also evident that the experimental group more often sought answers in the lab manual as opposed to asking other students which was still possible. Note that there was only one other student available to the experimental group (his/her lab partner) while the control group had either 10 or 12 other students in the room. This may indicate that the presence of others in the room, beyond the lab partner, may be a source of social interaction within a traditional face-to-face lab group. This may be important and future studies should focus on the types of social interactions that occur in the different lab formats.

With respect to the next question about how the participant solved problems, students in both groups answered similarly: most participants chose "I came up with a way to solve it" (4 for control; 5 for remote). The remaining two answers for the control group were “I had the opportunity to come up with a way to solve it, but was unable to” and the remaining one answer for the experimental group was “There was no way for me to figure out a way to solve it.” The numbers of responses for these remaining answers is too small to speculate on any importance.

When asked in the next question if they designed something *physical* to help solve a problem, both groups answered identically. Four answered that “there was no opportunity for me to design something physical” and the other two chose “I was able to design something physical.” Since there really was no opportunity for designing physical solution to problems in this particular lab, either these answers must be discounted or the question should be re-worded in future studies to be more clear. Since the two groups answered identically, there is no reason to speculate on any differences with respect to this question. On the other hand, it may be that because most answered that they had no opportunity to design something that the objective for students to “solve open-ended problems through the design and construction of new artifacts or processes” (Ma & Nickerson, 2006, p.8) is not being met. This would need to be confirmed in studies with larger sample sizes.

In general, neither group responded positively that they had experiences reflecting the design skills learning objectives as expressed in Nickerson and Ma’s model. This could be due to the nature of the lab itself. Lab design must include opportunities for these experiences to happen. Repeating this study with a variety of labs may reveal more experiences with this lab objective, or it may reveal that this lab objective is rarely met in lab science regardless of the lab topic. More research will need to be done to investigate this issue.

*5.4 Students’ Experiences with Respect to Professional Skills Learning Objectives*

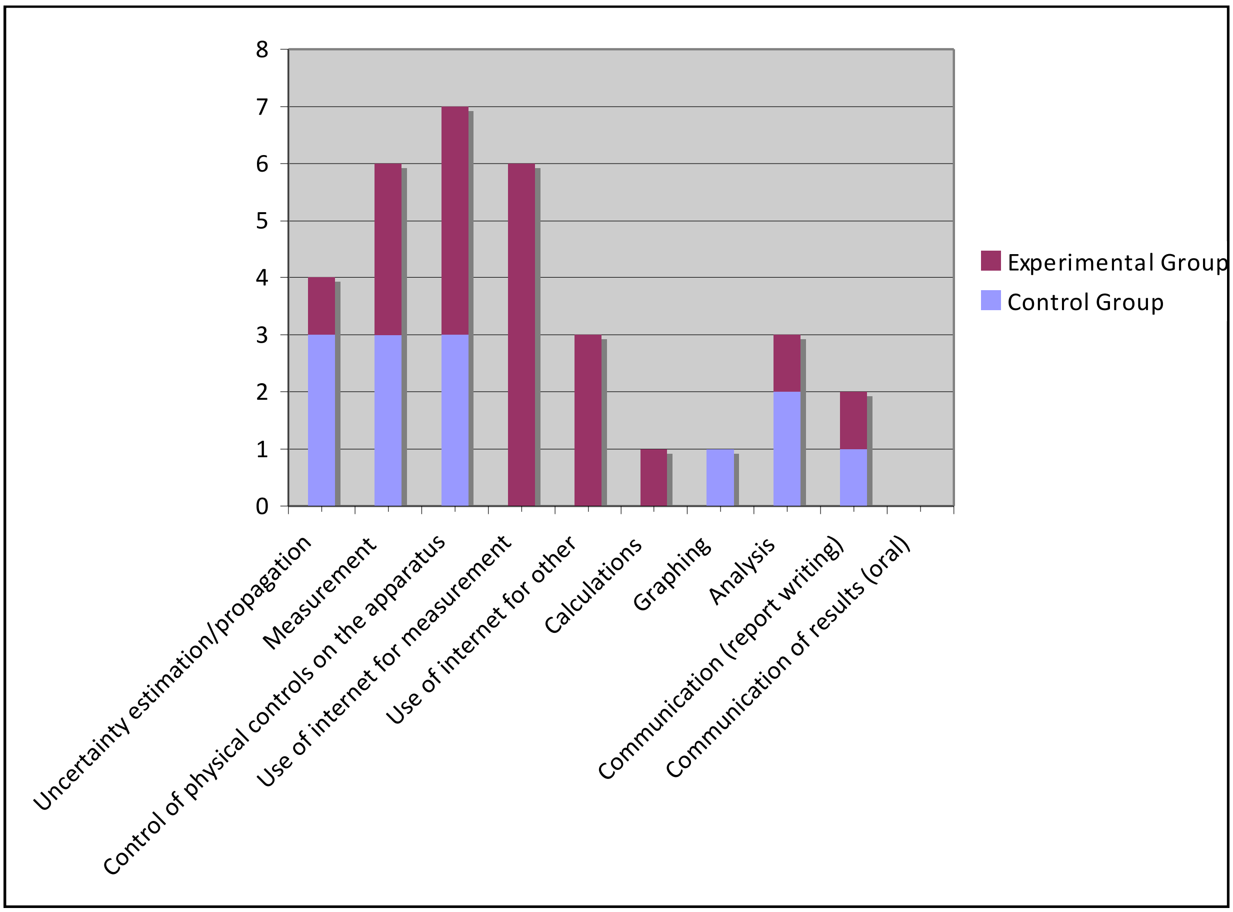
Table IV summarizes the responses by the participants when asked to “Please list the skills you became more familiar with. Note: you can select as many as you like (or none).” This table shows which skills individual participants chose which enables individual differences or patterns to be seen. The participants in the control group chose an average of 2 skills each, while the experimental group chose an average of 3.3 skills each. This difference may be important and may imply that the remote lab group felt that they had experienced more learning about professional skills than their control group counterparts. Further studies are needed.

Table IV Lab Skills Students Identified as Having Learned More about as a Result of Performing the Lab

| | Control Group: Hands-on Format | | | | | | Experimental Group: Remote Lab Format | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Participants | 1 | 2 | 3 | 4 | 5 | 6 | 1 | 2 | 3 | 4 | 5 | 6 |
| Uncertainty estimation/propagation | X | X | | | | X | | | X | | | |
| Measurement | X | | | | X | X | | X | | X | X | |
| Control of physical controls on the apparatus | | X | X | | X | | X | X | | X | | X |
| Use of internet for measurement | | | | | | | X | X | X | X | X | X |
| Use of internet for other | | | | | | | X | | | | X | X |
| Calculations | | | | | | | | | X | | | |
| Graphing | | | | | | | | | | | | |
| Analysis | X | | | | X | X | | | | | X | |
| Communication (report writing) | | X | | | | | | | X | | | |
| Communication of results (oral) | | | | | | | | | | | | |

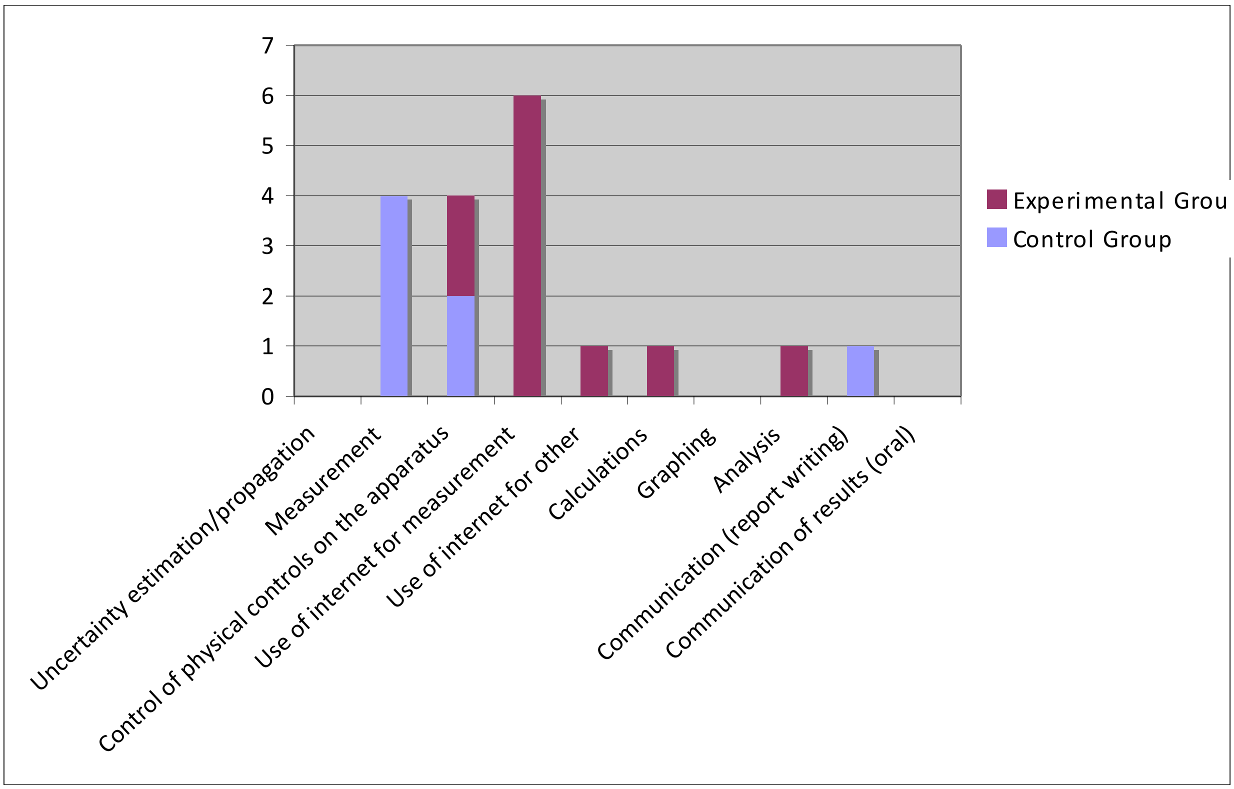
Figure I shows a comparison of the various professional lab skills identified by each group. While there were some differences between the groups, no difference stands out in this respect except for "Use the internet for measurement," which all of the remote format students chose and none of the hands-on students chose. While this may appear to be an obvious result, it may be important. If this is deemed an important professional skill to learn, then the remote web-based lab students may be at an advantage in this respect. There may also be a difference with the remote group choosing the "Use of internet for other" as more of the remote format students chose this one as well. It's possible that the remote group were required to use the internet to support their work more than the hands-on format students. Again, more studies would need to be done to investigate this fully.

Figure I Lab Skills Students Identified as Having Learned More about as a Result of Performing the Lab. The control group used the traditional hands-on lab format and the experimental group used the remote web-based lab format. The y-axis gives the number of students who identified the skill.



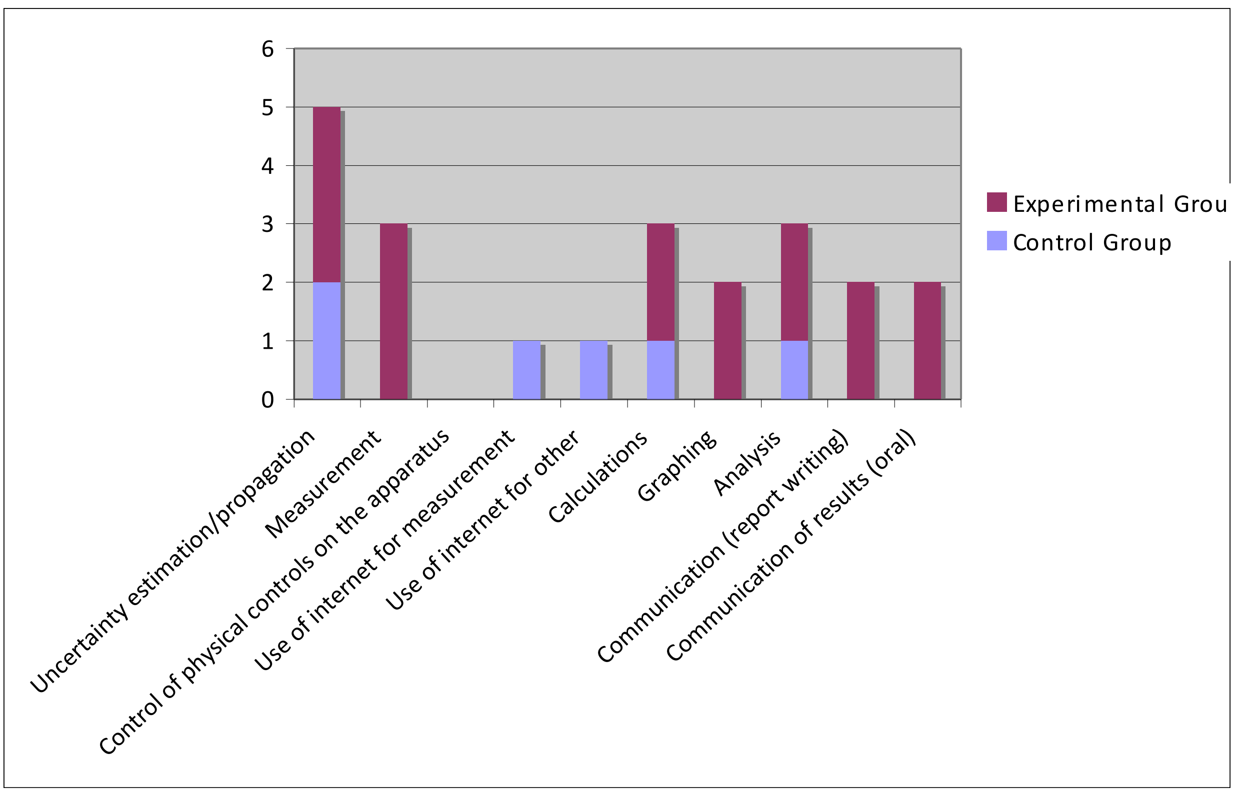
For the follow-up question: “Of the skills you chose [in the previous question], which did you learn the *most* about relative to what you already knew?,” the results are shown in Figure II. Of the skills that were identified to be the ones learned most about, there were more answer “b” (Measurement) for the control group and answer “d” (Use of internet for measurement) for the experimental group. Again, the “Use of internet for measurement” may be expected. The identification of “Measurement” more often by the control group may be of interest in future studies. If the control group believed that they were measuring things and the experimental group were not, then this may have important implications for learning.

Figure II Lab Skills Students Identified as Having Learned *Most* about as a Result of Performing the Lab. The control group used the traditional hands-on lab format and the experimental group used the remote web-based lab format. The y-axis gives the number of students who identified the skill.



For the second follow-up question asked: “Of the skills you chose [in the previous question], which did you learn the *least* about relative to what you already knew?,” the results are shown in Figure III. Compared to Figure II, both groups identified “Uncertainty Estimation/Propagation” more in Figure III. This may be explained by the fact the e/m the lab is positioned late in the semester and this skill tends to be focused on earlier in the semester, relatively speaking. As well, there are many more answers in general identified by both groups compared to Figure II. This may be of interest in future studies. One more difference stands out. Of the skills that were identified to be the ones learned least about as a result of performing the lab, “Measurement” was chosen more often for the experimental group, which may be important when the previous table is considered (where “Measurement” was chosen more often by the control group as a skill they learned most about). This seems consistent and may be pointing to an important difference. This may be of interest in future studies.

Figure III Lab Skills Students Identified as Having Learned *Least* about as a Result of Performing the Lab. The control group used the traditional hands-on lab format and the experimental group used the remote web-based lab format. The y-axis gives the number of students who identified the skill.



*5.5 Students' Experiences with respect to Social Skills Learning Objectives*

All participants in both the control group and the experimental group answered that they worked with a partner, except for two participants in the control group. These two students did however work with partners as the researcher confirmed through a follow-up conversation with the lab instructors. These two students proceeded to answer questions as if they had worked with partners as well, so it may be that the participants mistakenly answered that question incorrectly.

With respect to how the participants responded to "If you worked with another/others, which best describes your experience?," four participants from the experimental group answered "a" ("It allowed us to complete the task easier/better than had I done it alone") while only one in the control group answered this way (see Figure IV). The control group had very uneven answers and there were two answers of "c" ("It had no effect of my ability to complete tasks") and one "e" ("It made completing the tasks more confusing/difficult than had I done it alone"). From this data alone, it appears that the experimental group had more positive experiences of working with others than the control group. However, larger sample size studies would have to be done to confirm or deny this.

Figure IV Experiences identified as a result of working with another/others with respect to how it affected the participant's ability to complete the lab. The control group used the traditional hands-on lab format and the experimental group used the remote web-based lab format. The y-axis gives the number of students who identified the skill.

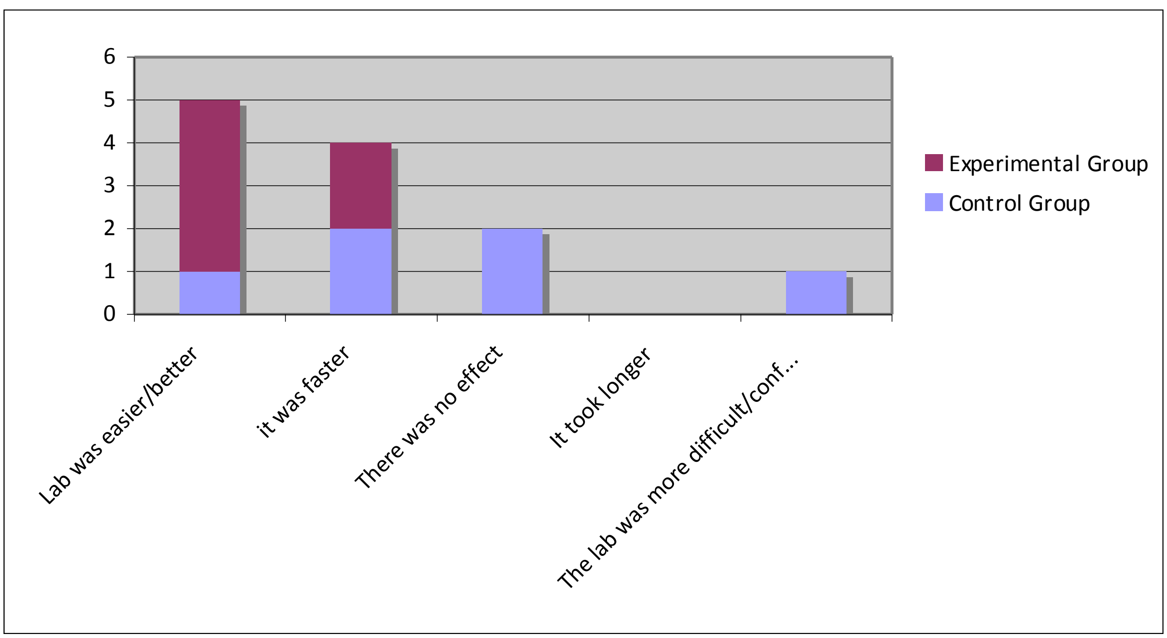
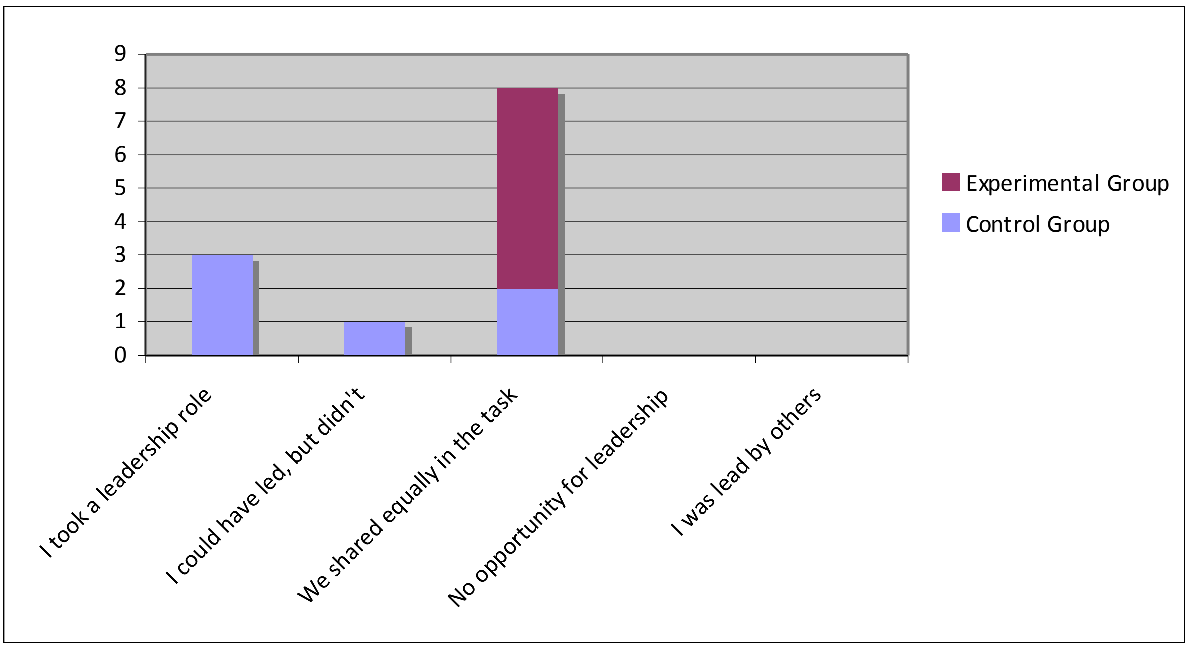


Figure V shows the responses of the two groups with respect to how they experienced leadership during the lab. All six of the participants in the experimental group answered “c” (“We shared equally in the task”), while the control group had varying answers including two participants who also answered “c”, three who answered “a” (“I took a leadership role”) and one who answered “b” (“There was an opportunity for me to lead, but I didn’t”). This may indicate a tendency for students using the remote web-based format to share more equally in the work in general, but once again, this may be attributable to the small sample size or that no difference actually exists. Again, further studies are needed.

Figure V. Experiences identified as a result of working with another/others with respect to leadership. The control group used the traditional hands-on lab format and the experimental group used the remote web-based lab format. The y-axis gives the number of students who identified the skill.




## Conclusions

*Limitations and Strengths*

There are some limitations to the design of this research study including the small sample size and that all students did not experience both lab formats (ideally, with order reversed for half of the participants) so that a paired t-test could be done. The participants came from two lab sections (of the same physics course), and the lab instructor was different for each lab section. Lab instructor should be controlled for in the future by choosing sections of labs with the same lab instructor. Also, descriptive statistics of the participants were not taken on the sample to allow comparison to the characteristics of the target population, and this limits the ability to make inferences from the sample to the target population of all post secondary lab science students.

On the other hand, the sample was chosen from the entire population of students for a standard first year physics course at an accredited Canadian university and variables between the control and experimental groups such as lab topic, lab procedure and equipment and the course instructor were controlled for. There are several other strengths in this study design in comparison to previous research on this topic. For example, this study was designed around a lab activity that has a high level of interactivity, media richness, real time data collection and an identical lab activity was used for both the control and experimental groups. Also, the questionnaire used was designed to investigate learning objectives as identified by a meta-analysis of lab objectives for a wide range of post-secondary science courses cited in the literature (Ma & Nickerson, 2006). Since previous research on this topic lacks these particular strengths, the results from this study provide a good starting point for a series of future studies that have the strengths of this design, but do not have the limitations mentioned above. This study design would be easily replicated with other sample populations within the target population and easily scalable to larger sized sample sizes which would strengthen the ability to make inferences to the target population.

*Future Direction*

In this research study, students conducting a physics lab using remote web-based technology and students using the traditional hands-on format were compared and no differences in effectiveness were found. There were some differences in the experiences of the participants with respect to certain lab learning objectives, but there was no indication that one format was superior in general. This research study, although done with an insufficient sample size to generalize to the population of all post secondary lab science students, provides a model that can be used for further studies in this area. If the results from other studies are found to be consistent with this one, they may provide evidence that remote web-based lab technology has the potential to be a useful tool for educators of science. This study also points to some of the areas that are of interest to explore, such as the inclusion of opportunities to design solutions for solving problems, the number and variety of professional skills practiced and the role of social interactions, including lab instructor presence. This in turn may inform the development of the technology (and labs themselves).

The advantages of remote web-based labs make this prospect worth exploring. The few studies that have been done, including this one, are promising. More research is needed to learn in which ways various formats for science labs are beneficial to student learning. Since there are other formats not looked at in this study, such as virtual labs involving simulations or learning objects, it would also be useful to study these formats to learn about their effectiveness. What is the relative effectiveness of simulation versus remote access of real equipment? Can users even tell them apart?

> There is disagreement over whether or not a simulated laboratory can be as effective in meeting objectives as remote access to an experiment consisting of physical equipment. This can be explored experimentally by having students evaluate the two kinds of experiences. It would be valuable to see if a

> student working over the Internet can tell the difference between a physical and a simulated experiment. Students could be asked to complete the online experiment and then indicate whether they thought they were dealing with real equipment or a simulation. It will be necessary to have user interfaces that appear to be operating real equipment but are really providing access to simulations. (Feisel & Rosa, 2005, p. 122).

If there are specific ways that learning lab science can be better facilitated by one format over another, it may even be useful to blend the different formats to optimize student learning. Nickerson (2007) has suggested that a *theory of appropriateness* be developed as a way to know when and under what circumstances remote web-based science labs, for example, should be chosen as a format for students' lab work.

> Generally, it may be possible to build a theory of appropriateness, in which for certain educational objectives certain technologies, with associated coordination processes, achieve educational goals more effectively. Right now, the evidence on which such a theory should be based is still scant, and without further research educators risk at the one extreme ignoring technologies which are cheaper and equally effective, and at the other extreme, dropping current labs in favor of less expensive but less effective technology. (Nickerson et al., 2007, p. 722)

These research ideas can be broadened to answer many other questions. Does the effectiveness of remote web-based labs depend on lab topics or subject areas (e.g., biology and chemistry)? Do student characteristics matter with respect to the lab format that is most effective (e.g., introverted learners, visual learners and more flexible learners)? Are there benefits to students who do collaborative lab work with students at different locations using remote web-based science lab technology? Does the access to more sophisticated instruments benefit learners? Do cultural differences matter for the effectiveness of remote web-based lab technology? What are student preferences with respect to the lab format (e.g., convenience, ease of setup and use, reliability, time commitment)? What are instructor and technician preferences? What features/affordances of remote web-based lab technology are important for meeting desired learning outcomes (e.g., real-time, fidelity, interactivity)? Are there any features that can be incorporated into remote web-based labs to increase their effectiveness beyond the traditional hands-on format (e.g., high speed cameras or tools for collaboration)?

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Appendix A A cross section remote web-based science lab projects worldwide

| Name | University/Learning Institution | Country | Reference/Literature |
|---|---|---|---|
| **PEARL** | Open University, University of Dundee, Trinity College, Universidade de Porto, Zenon SA | EU (UK, Scotland, Ireland, Portugal, Greece) | (Cooper, 2003) |
| **WebLab** | MIT | USA | (del Alamo, Brooks, McLean, Mishuris, Chang & Hui, 2003) |
| **RCL** | Technical University of Kaiserslautern | Germany | (Grober, Vetter, Eckert & Jodl, 2007) |
| **ReLI** | University of Colorado | USA | (Sicker, Lookabaugh, Santos & Barnes, 2005) |
| **RL** | Florida Atlantic University | USA | (Alhalabi, Marcovitz, Hamza & Petrie, 2002) |
| **MARVEL** | | EU | (Aliane, Martinez, Fraile, & Ortiz, 2006) |
| **ITLL** | Cornell | USA | (Ertrugrul, 1999) |
| **LABNET** | Universidad Europa de Madrid | Spain | (Aliane et al., 2006) |
| **TLR** | University of Tuebingen | Germany | (Harms, 2000) |
| **I-Lab** | Learning Lab of Lower Saxony | Saxony | (Bohne, Faltrin & Wagner, 2002) |
| **SBBT** | Oregon State University | USA | (Harms, 2000) |
| **IRLE** | Rutgers University | USA | (Ogot, Elliott & Glumac, 2003) |
| **IECATS** | Indiana University Southeast | USA | (Forinash & Wisman, 2005) |
| **NetLab** | University of South Australia | Australia | (Nedic, Machotka, & Nafalski, 2003) |
| | Stevens Institute of Technology | USA | (Esche, 2006) |
| **ISES** | University of Trnava, University of Zlin and Charles University | Slovak/Czech Republics | (Schauer, Ozvoldova & Lustig, 2008) |
| **CyberLab** | Stanford University | USA | (Hesselink, Rizal & Bjornson, 2000) |
| **PCOL** | Purdue University | USA | (http://www.chem.purdue.edu/gweaver/projects/ pcol.html) |
| **RWSL** | North Island College | Canada | (http://rwsl.nic.bc.ca/about.html) |

Appendix B Student Questionnaire

**Did you perform the e/m lab in person or remotely?**

- In person (in the regular lab setting)
- Remotely (Labview)

**Educational Goal Category: Conceptual understanding (Q 1-3)**
**Extent to which laboratory activities help students understand and solve problems related to key concepts taught in the classroom.**

**1) In this lab, you saw that the effect of a magnetic field on a beam of electrons. Of the following, which best describes what you experienced?**

a I understood that increasing the magnetic field bent the electron beam into a circle for the first time
b The lab confirmed what I expected, that the magnetic field bent the beam into a circle
c The fact that the magnetic field bent the beam into a circle surprised me, and I didn't understand why it happened
d I didn't observe that the increased magnetic fireld affected the electron beam
e I was confused by what happened to the electron beam when the magnetic field increased

**2) In this lab, you saw that by increasing the voltage across the anode and cathode of the electron gun that the radius of the circular electron beam increased. Of the following, which best describes what you experienced?**

a I understood that increasing the voltage increased the energy of the electron for the first time

b Seeing the beam radius increase with increased voltage confirmed what I already knew

c The fact that the increased voltage increased the radius of the beam circle surprised me, and I didn't understand why it happened
d I didn't observe that the increased voltage affected the electron beam

e I was confused by what happened to the electron beam when the voltage increased

**3) In this lab, you saw that by increasing the current in the Helmholtz coils that the radius of the circular electron beam increased. Of the following, which best describes what you experienced?**

a I understood that increasing the current bent the electron beam into a circle for the first time

b The lab confirmed what I expected, that the increased current bent the beam into smaller circle

c The fact that the increased current idecreased the radius of the beam circle surprised me, and I didn't understand why it happened
d I didn't observe that the increased current affected the electron beam

e I was confused by what happened to the electron beam when the current increased

**Educational Goal Category: Design skills (Q 4-6)**
**Extent to which laboratory activities increases student's ability to solve open-ended problems through the design and construction of new artifacts or processes**

**4) There are likely a number of problems you encountered during this lab. Of the following, which best describes what you experienced?**

a I was able to create and apply my own solution to at least one problem
b There was only one solution possible and I figured out a way to solve the problems on my own without help from the manual or others
c I re-read the manual to figure out the solution
d I asked the lab instructor or other students for the solution
e I was generally unable to solve my problems

**5) With respect to *any* problem you encountered, which of the following best describes your experience?**

a I came up with a way to solve it
b I had the opportunity to come up with a way to solve it, but I wasn't able to
c There was no opportunity to figure out a way to solve it

**6) With respect to *any* problem that you encountered, which of the following best describes your experience?**

a I was able to design and construct something (physical) to solve it
b I had the opportunity to design and construct something (physical) to solve it, but I wasn't' able to
c There was no opportunity for me to design and construct something (physical) to solve it

**Educational Goal Category: Professional skills (Q 7-9)**
**Extent to which students become familiar with the technical skills they will be expected to have when practicing in the profession**

**7) Please list the skills you became more familiar with. Note: you can select as many as you like (or none).**

a Uncertainty estimation/propagation
b Measurement
c Control of physical controls on the apparatus
d Use of internet for measurement
e Use of internet for other
f Calculations
g Graphing
h Analysis
I Communication (report writing)
j Communication of results (oral)

**8) Of the skills you chose in Question #7, which did you learn the *most* about relative to what you already knew?**

- a Uncertainty estimation/propagation
- b Measurement
- c Control of physical controls on the apparatus
- d Use of internet for measurement
- e Use of internet for other
- f Calculations
- g Graphing
- h Analysis
- I Communication (report writing)
- j Communication of results (oral)

**9) Of the skills you chose in Question #7, which did you learn the *least* about relative to what you already knew**

- a Uncertainty estimation/propagation
- b Measurement
- c Control of physical controls on the apparatus
- d Use of internet for measurement
- e Use of internet for other
- f Calculations
- g Graphing
- h Analysis
- I Communication (report writing)
- j Communication of results (oral)

**Educational Goal Category: Social Skills (Q 10-12)**
**Extent to which students learn how to productively perform engineering-related activities in groups**

**10) Did you complete any task with another/others during this lab?**

- a Yes
- b No

**11) If you worked with another/others, which best describes your experience?**

- a It allowed us to complete the task easier/better than had I done it alone
- b it allowed us to complete the task faster than had I done it alone
- c It had no effect of my ability to complete tasks
- d It made completing the tasks take longer than had I done it alone
- e It made completing the tasks more confusing/difficult than had I done it alone

**12) If you worked with another/others, which best describes your experience?**

- a I took a leadership role
- b There was an opportunity for me to lead, but I didn't
- c We shared equally in the task
- d There was no opportunity for leadership
- e I was lead by other(s)

Experiment 12

**DETERMINATION OF $^{e}/m$**

Around the turn of the century, two dramatic experiments established the existence of the electron, a charged particle very much smaller than an atom in size and in mass. In 1897, J. J. Thomson analyzed the motion of cathode rays (electrons) as they passed through electric and magnetic fields. Thomson's investigations gave the following results:

1) The rays consist of particles that have a negative electric charge and a definite mass.
2) The charge-to-mass ratio of the electron was very large, about 2000 times that of a hydrogen ion, the lightest known ion.

From the second result, one can conclude that either the charge on the electron is very much bigger, or its mass very much smaller, than the hydrogen ion. Thomson believed that the latter was the case. Sometime later (around 1909), R.A. Millikan measured the charge on the electron and thereby confirmed Thomson's suspicions.

### Objective

To determine the $^{e}/m$ ratio from the graph expressing the relationship between electron accelerating voltage and current in Helmholtz coils for an electron beam with constant radius.

### Theory

In this experiment, electrons are "boiled off" a heated cathode inside a specially designed tube (filled with helium at a pressure of about $10^{-2}$ mm of Hg), and then accelerated by a high potential difference between the cathode and anode. The kinetic energy gained by the electrons as they reach the anode is equal to the work done on them by the electric field, i.e.,

$$\frac{1}{2}mv^2 = qV \tag{1}$$

where *m* is the mass of the electron, *v* is the velocity of the electrons, *q* is the charge of an electron and *V* is the voltage between the electrodes that is used to accelerate the electrons.

The electron beam emerges from a small aperture in the anode and enters a homogeneous (uniform) magnetic field produced by a pair of Helmholtz coils (described below). The magnitude of the force *F* that the magnetic field exerts on the electron beam, as the beam enters the magnetic field *B* at an angle □□□is given by

$$\begin{aligned} &\vec{F} = q\vec{v} \times \vec{B} \\ \text{or,}\quad &F = qvB\sin\theta \end{aligned} \tag{2}$$

If the electron beam is directed **perpendicular** to the magnetic field of the coils, then the magnetic force will be perpendicular to the direction of the beam. Thus, the magnetic force changes the beam's direction of motion; it does not change its speed.

Furthermore, because the magnetic field is uniform, the magnetic force and, consequently, the beam's acceleration are not only always perpendicular to the direction of motion, but they also have constant magnitudes. These are precisely the characteristics of a particle moving in uniform circular motion. The equation stating that the magnetic force provides the acceleration is given by

$$qvB = \frac{mv^2}{r} \tag{3}$$

where *r* is the radius of the circular path of the electron beam.

Combining Equations (1) and (3), we obtain an expression for the electron charge-to-mass ratio $^{e}/_{m}$:

$$\frac{e}{m} = \frac{2V}{B^2 r^2} \tag{4}$$

where the symbol *e* has been substituted for *q*.

All but the magnetic field strength *B* in Equation (4) are directly measurable. *B* can be resolved into directly measurable quantities by considering the geometric symmetry of the Helmholtz coils. The coils consist of two individual coaxial, circular coils, each of radius *R*, which have their planes parallel and separated by a distance equal to *R*. When current is put through the coils, an almost uniform magnetic field is produced over a fairly large region near the centre of the axis of the coils. The calculus solution for the value of the magnetic field at a distance *X* along the axis of a single loop of radius *R* carrying a current *I* is

$$\mathrm{B} = \frac{\mu_0 \mathrm{I} \mathrm{R}^2}{2\left(\mathrm{R}^2 + \mathrm{X}^2\right)^{3/2}}\,. \tag{5}$$

where $\mu_O$ is the permeability of free space ($\mu_O = 4\pi \times 10^{-7}$ Tm/A).

Since there are *N* current loops in each coil arranged such that their fields add constructively and contribute equally at the centre of the tube, the total coil field is then

$$B = \frac{\mu_0 N I R^2}{\left(R^2 + X^2\right)^{3/2}}\,. \tag{6}$$

At the centre of the axis of the Helmholtz coils, *X* = *R*/2, and Equation (6) simplifies to

$$B = \left(\frac{8}{\sqrt{125}}\right)\left(\frac{\mu_0 N I}{R}\right) \tag{7}$$

(We may safely assume that this value of *B*, derived from the central point on the axis of the coils, closely approximates *B* at the position of the electron beam.) Substituting $\mu_O = 4\pi \times 10^{-7}$ Tm/A, *N* =130, and *R* = 0.15 m into Equation (7) gives

$$B = (7.793 \times 10^{-4}\ \tfrac{T}{A}) I \tag{8}$$

where *B* is in tesla (T) when *I* is in Amperes (A).

Substituting Equation (8) into Equation (4), an experimentally measurable value of *e/m* can be obtained from

$$\frac{e}{m} = \frac{2V}{(6.073\times10^{-7}\ \frac{T^2}{A^2})I^2r^2} \tag{9}$$

Since there are three data variables *V*, *I*, and *r*, three different linear plots can be made to verify Equation (9). However, due to the limitations of time and the design of the equipment, you will plot only the relationship between *I* and *V* (i.e., *r* is held constant at some fixed value). Rewriting Equation (9) gives an equation that can be experimentally tested and from which the $^e/_m$ ratio can be determined

$$V = \left(\frac{1}{2}\frac{e}{m}(6.073\times10^{-7}\ \frac{T^2}{A^2})r^2\right)I^2 \tag{10}$$

The accepted value of $^e/_m$ is $1.7588\times10^{11}$ C/kg.

**Apparatus** Nakamura (B10-7350) e/m experimental apparatus
BK Precision Discharge Tube Power Supply – Model 1511 (±1%)
Fluke DMM (± 0.2%)
table lamp

The Nakamura $^e/_m$ experimental apparatus consists of a specially designed tube (filled with helium at a pressure of about $10^{-2}$ mm of mercury) supported at the centre of a pair of large, parallel-mounted Helmholtz coils (see Figure 1). Within the spherical tube is an electron gun that is composed of a heated cathode (a heated filament is attached to the cathode), a focusing element, and a coaxial anode containing a single hole. The path of the narrow beam produced by the electron gun is visible due to the glow discharge caused by ionizing collisions between electrons and the helium gas inside the tube. To ensure a satisfactory circular beam, the electron path is perpendicular to the axis of the Helmholtz coils. There is a scale inside the tube for measuring the diameter of the path traced by the electron beam.

Connect the jacks of the e/m apparatus that are labelled HEATER to the output voltage 6 (red and blue jacks) of the FILAMENT SUPPLY on the discharge tube power supply. Polarity doesn't matter, as this is an AC voltage. This heats up the filament so that the electrons are, in effect, "boiled off" the anode.

The 0-500Vdc jacks on the discharge tube power supply provide up to 500 V for the accelerating voltage between the cathode and anode. Connect the jacks of the e/m apparatus that are labelled ANODE to the 0-500Vdc jacks on the discharge tube power supply (**red to red** and **black to black**), and make sure the **VOLTAGE MONITOR SELECT switch is set to the left**.

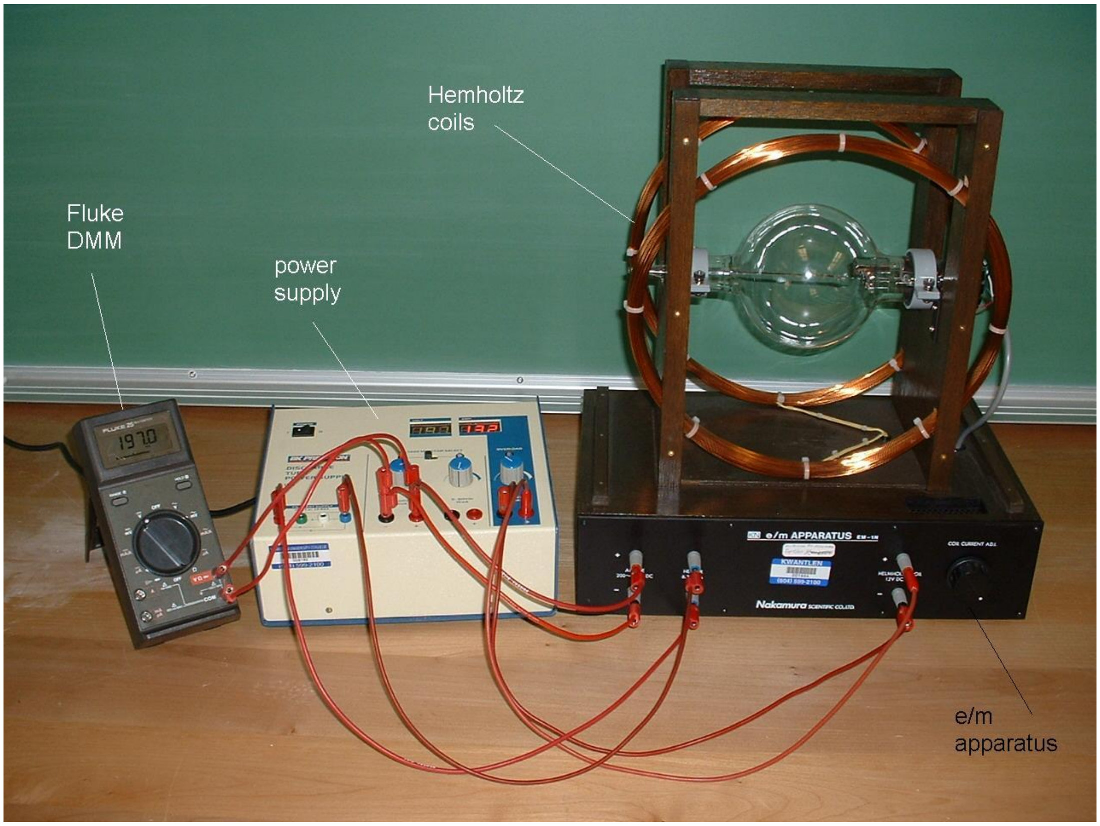


**Figure 1** e/m apparatus

Attach the Fluke DMM across the 0-500Vdc jacks on the discharge tube power supply. You will measure the voltage from the DMM, as it provides greater precision than when read directly from the power supply.

The 0-20Vdc 5A MAX jacks on the discharge tube power supply provide the current *I* to the Helmholtz coils. Connect the jacks of the e/m apparatus that are labelled HELMHOLTZ COIL to the 0-20Vdc 5A MAX jacks on the discharge tube power supply (**red to red** and **black to black**).

**Procedure**

| |
|---|
| **Caution: Do not leave the beam striking the surface** of the tube for a prolonged period of time: it can take less than 3 minutes for the beam to bore a hole through and ruin the tube! Leave it deflected into a circular path, or turn off the accelerating voltage if you are not making any measurements. Also, **do not leave the power supply on at high voltages** for extended periods of time, as they tend to "burn out." |

1) Set up the apparatus as described in the apparatus section. Turn the COIL CURRENT ADJ knob on the Nakamura e/m apparatus fully clockwise. The 0-20Vdc 5A MAX jacks on the discharge tube power supply provides the current *I* to the Helmholtz coils. **Do not exceed 12 V or 2 A,** since these are the maximum ratings of voltage and current for the coils. The 0-500Vdc jacks on the discharge tube power supply provide up to 500 V for the accelerating voltage, but the Nakamura e/m apparatus is rated to be accurate only for V = 200-500V.

2) Starting with V ≈ 200V, determine the current that produces a circular beam path with a diameter as large as possible (approximately 9-10 cm, but 11cm is too high for good results) so that the uncertainty of *r* will be relatively low (**the scale visible in the tube measures the diameter in cm**). Record the diameter *d* of the beam path. Choose 6-8 approximately equal increments of voltage that cover the 200-500V range and, for each V, adjust the current *I* until the beam path returns to the original diameter *d*. Record *I* and *V* each time (*I* can be read off the power supply, but use the DMM to measure *V* for the greater precision it allows).

3) Plot a graph to verify Equation (10), and determine $^{e}/_{m}$ from the graph. Note: when using scientific notation, record the value and its uncertainty to the same power, e.g., $(7.55 \pm 0.03) \times 10^{6}$ m.

## GRADING POLICY

In science and math courses we often claim that our marking is completely objective; either a fact is stated or it is not, an answer is right or wrong, a principle is either confirmed or not supported in an experiment, and thus our marking is straightforward and a good reflection of the student's understanding. With lab reports this is no longer true. While we look for reasonable experimental results, this is only one of the factors which contribute to a good lab report, and marking is largely influenced by impression. The following grading description should give you some guidelines as to how the lab reports are graded:

| | |
|---|---|
| 10/10 | The lab report borders on perfection in all aspects:<br>- clarity and organization of presentation<br>- excellent experimental values<br>- incisive discussion and results<br>- original contribution such as variation of the method, a cross-check procedure, a particularly good discussion of uncertainty and how it could be reduced |
| 9/10 | The experiment and write-up are done exceptionally well<br>- there is depth in understanding exhibited in the discussion |
| 8/10 | This is an A mark! Format is clear and complete, data and results are good and well explained, conclusions are complete and clearly and concisely stated, and there are no mistakes of consequence. In general, entire report is complete and correct |
| 7/10 | Most work is done correctly, but is not clearly organized and/or there is the odd minor mistake<br>- not enough labelling and explanation<br>- careless arithmetic<br>- careless graphing |
| 6/10 | There are several minor mistakes *or* one important part of the analysis has been misunderstood or omitted *or* the presentation is very difficult to follow<br>- poor treatment of uncertainty and significant figures<br>- poor treatment of graphs and their analysis |
| 5/10 | Much of the experimental work is satisfactory, but there are two major omissions or misunderstandings, or one major omission and a very poor presentation |
| 4 or less | There are several major omissions or misconceptions, experimental work is faulty, and/or the presentation is extremely difficult to follow |

It is not our intent to penalize you for faulty apparatus. If you are having problems, notify the lab instructor at once.

**Note that *clarity* and *organization* are important, but that *neatness* has not been mentioned explicitly. A lab notebook is expected to contain all the false starts, bad runs, and mistakes that occurred. Cross these out neatly and carry on; don't waste time recopying.**