Physics Education Research – A Comprehensive Study

by

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Abstract

This project focuses on Physics Education Research (PER), and studies both the underlying theory and several practical applications. A summary of relevant pedagogical and PER-specific publications is first presented. Practical applications of the outlined principles are then studied, in the context of the Physics for Life Sciences course (PHY 138) at the University of Toronto. The effectiveness of the techniques used in PHY 138 is evaluated; and, teaching techniques used in large-lecture settings at major Canadian universities are compared.

In addition to the above theoretical study of PER, a more experimental analysis is conducted. An instructional-laboratory experiment is developed to teach concepts relating to RC circuits; and, two separate approaches to teaching the concepts are implemented. Student achievements on conceptual tests, both while performing and after completing the laboratory experiment, are analyzed, in order to determine the effectiveness of the teaching approaches. Neither approach was found to be significantly effective at teaching the students about RC circuit. Possible explanations of these results, as well as possibilities for further study, are presented in conclusion.

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The author would like to acknowledge one more person. Gila Ashtor –

Such wilt thou be to me, who must,
Like th' other foot, obliquely run;
Thy firmness makes my circle just,
And makes me end where I begun.

– John Donne

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List of Symbols and Definitions

- The term “Introductory level courses” refers to first-year university courses.
- The acronym “PER” stands for Physics Education Research.
- The acronym “MER” stands for mainstream education research.

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Introduction

Physics Education Research (PER) is a relatively new field of academic study, and its leading practitioners have founded it through their work over the past three decades[1]. The roots of PER, however, far predate its present branches, as it stems from the two professions of pedagogy, in general, and of physics instruction, in particular.

The use of “physics instruction,” above, as opposed to “physics education,” signifies a relevant distinction. It is the goal of PER to improve existing techniques and to innovate new methods of teaching physics. The practitioners of PER aim, in their work, to make physics instruction synonymous with physics education – that is, they purpose to maximize the educational value and the teaching effectiveness of instructional practices employed in physics classrooms, at all academic levels.

The difference between the educational value of a particular approach and its teaching effectiveness is more than merely semantic. Herein, educational value is considered from a holistic perspective, and refers to all that is gained by a student in terms of factual knowledge, conceptual understanding, functional proficiency and also attitude and lasting impression relating to a particular field of study. Teaching effectiveness, in contrast, speaks of those benefits explicitly measured through evaluation; and, while often quantitatively precise, the accuracy of measures of teaching effectiveness is subjective with regards to the specific testing procedures implemented. Conversely, the only complete measure of educational value, most likely, is former students’ future achievements in their respective fields.

In the first half of this report, PER practices are investigated, both in order to learn how the research is conducted – its appropriate investigative environment and the apparatus used – as well as to evaluate the types of physics teaching techniques in large, introductory-level university classes. The term educational value will be used more loosely than as specified above, to acknowledge that, though true educational value cannot be measured in the short term, if at all, many factors ascribe success to teaching practices – not only students' grades. The terms physics instruction and physics education will often be used interchangeably, in acknowledgement of the successes achieved to date by the rigorous, scientific investigations of PER practitioners worldwide.

The first half is broken into three main parts, as follows. First, relevant aspects of the underlying theoretical background of PER, specifically, and of mainstream education research (MER), in general, are discussed. Second, an evaluation is conducted of the teaching practices employed in the Physics for Life Sciences course (PHY 138) at the University of Toronto, which have been developed though the work of Harrison and Pitre, among others. Third, introductory-level teaching techniques used in physics departments at major Canadian Universities are enumerated, drawing from the recent publication of Alan Slavin, from Trent University.

The second half of this report summarizes a study performed regarding the application of PER theory in an introductory physics laboratory. An exercise was developed, guided by PER principles discussed in the first section, and was performed by a sample of students in the PHY 138 course. PER techniques were also used to gauge student learning. The laboratory exercise is examined, its motivating principles are revisited, and results obtained from student test results are analyzed.

This report is the culmination of work in a year-long, undergraduate thesis project, as mandated by the curriculum of the fourth year of the Physics Option of the Engineering Science program. The topic was chosen by the author, and the method of approach was formulated through the advice and direction of Harrison and Pitre. Harrison and Pitre supervised and guided the author over the duration of this project.

Motivation for Study

PER is about communicating physics in an educational manner. At its core, the field focuses on spreading physicists' interest and enthusiasm for their work to students of the science – those who intend to become future physicists and those aspire to other goals, alike. PER strives to teach physics, and it is driven by the beliefs not only that physics is immediately relevant in every persons' life, but also that an understanding of physics enriches people's lives.

In the modern era of post-secondary education and its relevance in society, more people are going to university and college and realizing the opportunities, both personal and professional, that formal education awards. Educational institutions now have a compounded responsibility, both to maintain their educational standards in the midst of swelling class sizes, as well as to re-invigorate their academic programs in order to cater to a different type of student body. The students of today are individuals with typically very different backgrounds and with drastically evolved goals, than those of previous generations of learners.

One important facet of PER is the study of how physics can be effectively taught to large classes, and with limited resources. Early models of teaching science, in general, took a more apprenticeship-focused approach[2]; and, physics, in particular, has an intrinsic experimental side that should guide a significant part of any introductory physics curriculum. Also, physics teachers at all levels have observed the pedagogical limitations of the lecture setting[3]; and, effective physics education, whether experimentally or theoretically focused, is especially demanding of instructional techniques that break out of the mould of a standard classroom. In addressing these challenges, PER practitioners have succeeded at transmitting both the level of energy and the student engagement of the apprenticeship setting into the large-class environment.

A more long-standing issue addressed by PER is the need for students to develop a conceptual understanding of physics[4], rather than merely the ability to solve problems.

This concern has become graver in current educational settings, because the burdens of marking numerous short-answer questions have prompted a tendency towards multiple-choice or purely quantitative questions on tests. PER focuses both on devising ways of teaching more accurate, complete and understandable models of physics to students, as well as upon creating appropriate methods of evaluation[5] of students' levels of conceptual understanding.

An especially important factor in PER is that the aforementioned motivations for work in the field are modulated by an appreciation of the need to conduct research in a rigorous, scientific manner. This demand for scientific rigor is one factor that places PER within the mandate of university physics departments[6], as opposed to in departments of philosophy or of education. There is often a stigma, albeit largely untrue, that educational studies should be categorized as "soft science."[7] Nonetheless, physicists who study educational techniques conduct their work as physicists, and this ascribes scientific credibility to their results. The goal to teach physics more effectively, to larger audiences and at first-rate standards, depends on the mantra that teaching, both generally as well as specifically related to physics education, is "a science as well as an art."[8]

Theoretical Background

Introduction:

PER, like physics research in general, has both theoretical and experimental foundations. While these two frameworks for study share a symbiotic relationship in the investigation of natural physical phenomena, they are often more loosely connected in pedagogical realms. This is because mathematical formulations, which model many natural processes, cannot be as strictly applied in relation to pedagogical theories. Nonetheless, PER is founded on theory, which is developed and tested through experimentation in teaching.

This report will not explicitly consider PER in comparison to other areas of research in the natural science, other than mentioning two things. Firstly, the studies conducted herein, as well as those referenced, both uphold the rigorous standards of scientific research in their practical aspects, which includes operating on the basis of solid theoretical foundations. Secondly, PER study, like that of general physics research, properly belongs within university physics departments.

In developing the theoretical background for the present study, certain general principles will be established. In doing so, reference will be made to modern interpretations of Dewey's relevant pedagogical theories. Focus will then be directed to physics education, specifically. The purpose and scope of PER will be considered, as will be theories and techniques of lecturing, in addition to structures developed for tutorials and laboratories. The pedagogical purpose of physics laboratories will be examined with particular focus, as will practical manifestations of pertinent theories. Later in this report, a separate study of PER principles in introductory physics laboratories will be conducted, and it will draw from the tenets outlined herein.

Pedagogical Theory:

The purpose of teaching is to teach. This is an obviously trivial statement. Its implications, however, are what have driven pedagogical theorists since Plato's time. The only meaningful evaluation of the success of a particular teaching strategy is the effectiveness with which the students learn the subject matter[9] through it. And, while a multitude of different approaches have been taken towards accessing this effectiveness, the basic, initial tenet has not changed with time. The purpose of teaching is to teach.

Dewey achieved much renown from his teaching philosophies, which strive to find a median between the authoritarian, knowledge-focused ideas of Plato with the opposite, student-centred approach of Rousseau. Dewey's pedagogy informed many schooling practices used today, and interpretations of his ideas continue to find relevance in many levels of education. His pedagogy is founded on the basis of Education Aims[10], which must be developed dynamically by the teacher, with regards to the needs of individual students. These aims edify a realistic structure grounded in reality, upon which teachers and students can effectively communicate in educational dialogue.

Dewey's emphasis on considering the student when teaching is reflected in his ideas concerning apprenticeship. By apprenticeship, Dewey means active, introductory research in a field, guided closely by an established practitioner. Although the intimacy of this teaching arrangement is often unfeasible in universities today, due to the number of students, the underlying principles can still inform practice in such settings. Dewey recognizes the effectiveness of an active and engaging learning environment. The student, in order to learn, must interrelate the external concepts with her/his internalized experience and understanding[11]. Dewey's ideal for any educational setting, whether in a university lecture hall or in a small laboratory, is a dynamic learning environment, in which the student not only is engaged through interaction with teachers, peers and with the subject matter, but also is able to adjust the transmission of information – ie, the teaching process – to match her/his pace and comprehension level. Such adjustment is facilitated, in Dewey's model, by simple activities: asking a question, discussing a concept with colleagues, repeating an experimental run, etc.

In his work, Dewey lays the initial foundations for the more recent idea of active learning[12]. In modern language, Dewey's pedagogy loses nothing in translation. The role of the teacher is to create an active learning environment, in which the student is engaged in the subject matter and stimulated to make links between observation and understanding. Interaction with a practitioner, teacher or instructor is essential to the active learning process. The apprenticeship approach, outlined by Dewey, provides a working, albeit outdated, model for actual teaching practice that aims to foster an active learning environment.

Another important aspect of Dewey's apprenticeship methodology is the human connection implicit in it. There is a certain energy derived from the enthusiasm of a practitioner for her/his work that enriches the learning experience. The importance of enthusiasm in teaching is explicitly recognized by Harrison, from the University of Toronto, with reference to introductory physics lectures[13]. Harrison considers the function that a physics lecture actually serves. The standard lecture setting is too impersonal to be directly interactive, and too linear and rapid to be explanatory. As he writes: "students do not actually learn in a lecture, but something related to the learning process is clearly occurring[14]". He determines that the physics lecture serves both a contextualizing role and also a motivational purpose.

The standard physics lecture, as a straightforward dissemination of information from teacher to student, is a major area of focus in PER. As Harrison points out, it is not an overly effective mechanism for teaching physics concepts[15]. Physics does not require strong memorization skills; rather, its analytical nature necessitates facilitation of effective explanation of the subject matter and allowance for student interaction with it.

The lecture, alone, acts to introduce and maintain student focus on the concept under study. The concept itself is typically learned through other means; but, the relevance of the concept within its larger context, and its relation to other concepts studied in the course, is given in the lecture. Moreover, as Harrison highlights, the enthusisasm shown by the lecturer for the subject matter is communicated to the students, and it lends to the development of a positive impression of physics in their minds. It is evident, hence, that an active learning environment involves both active engagement of the students, and also energetic activity on the part of the teacher. Teaching is, in part, an inspirational process; the teacher both gives access to and presents the relevance of the subject matter, as well as motivates the students to learn it.

At its core, Harrison's work recognizes the complexity of the process involved in learning any subject. For physics, specifically, the aforementioned analytical nature of the field adds a level of difficulty to what is required for effective teaching. These challenges lend emphasis to the argument that PER must be conducted within university physics departments, as well as from an interdisciplinary approach that draws on the work of other academic faculties[16].

To discuss the latter point first, progress in PER cannot be easily made if the research is conducted without regard to pedagogical theories in general. The PER group at the University of Sydney argues that MER principles are relevant in the development of physics teaching methods. One immediate benefit is the sheer amount of work that has been done in pedagogical theory in general, on a wide breadth of topics. While PER has flourished through the past thirty years, educational theorizing has occurred for centuries, and a wealth of important work has been done.

Two examples of areas of overlap between the two fields – PER and MER – concern procedures for developing educational theory and mechanisms for evaluating the effectiveness of resulting practice. Dewey contributes a specific example to the former, in that he developed his theories through dynamic application of them in practical settings[17]. So, too, should PER theories be developed – that is, in tandem with implementation. Another principle transferable from MER is the importance of accurate evaluation methods. In PER, one popular method for gauging the effectiveness of a particular theory is the use of pre-testing and post-testing[18]. Students are tested before and after experiencing some prototype teaching method, and improvement is measured via comparison of the two sets of test scores.

While useful, PER researchers should be wary of employing MER-developed theories verbatim in their work. The specifics of physics - its analytical nature, expression through mathematics and underlying conceptual framework - require sensitivity to how things are taught and how evaluative results are interpreted. To ensure appropriate implementation of pedagogical theory in teaching physics, PER belongs in university physics departments[19], in the hands of experienced physicists. Moreover, this localization allows easy integration of theorizing with practical experimentation. In short, it is important that PER be practiced by physicists, and that a holistic approach to education is upheld by these practitioners through the process.

Cognitive Pedagogical Theory:

Good theories of teaching are necessarily contingent upon observation of how people learn new concepts, and on how people understand those concepts already known. Dewey's pedagogy is based on an abstract model of human understanding[20]; and, though outdated, his theory corresponds with more recent investigations in the field of cognitive science. Dewey's fundamental claim is in opposition to a preceding idea, primarily supported by John Locke, that the human mind can be initially treated as a "tabula rasa," a blank slate[21]. Dewey reasons, instead, that upon entering the classroom, the student already has an individual cognitive makeup[22]; hence, to teach the student effectively, curriculum must be catered to each perceptive palate, rather than served in a pre-prepared, student-independent manner.

As argued earlier, PER should borrow from mainstream educational theories; however, it must be addressed specifically towards physics and the nuances of the field. (This stands nicely in analogy to how teaching, in general, needs to be customized to the students.) Edward Reddish, from the University of Maryland, has studied cognitive theory, and has made important findings in the way that people learn and understand physics. In his paper, "Implications of Cognitive Studies for Teaching Physics" (1994), he incorporates Dewey's original objection to the Tabula Rasa model, and offers a tangible framework, on which instructional techniques can be developed.

As Reddish emphasizes, "students are not blank slates"[23]; and, their prior experiences and preconceived understandings comprise the structure through which new information is perceived. Moreover, the human mind constructs intricate "mental models" from the notions it remembers. These models are, in essence, the way we see the world; they not only formulate explanations of the phenomena our senses perceive, but they also govern our approach to certain situations – including those pertaining to the learning environment[24]. For example, as many an introductory-level university professor would relate, most students enter such courses with inaccurate or incomplete understandings of physical phenomena. Also, perhaps more problematic, students often approach their physics courses in a manner not conducive to gaining conceptual understanding.

As an example, Reddish cites difficulties in teaching students about Newton's Law of Inertia[25]. Because friction is prevalent in students' everyday experience, they cannot easily grasp the idea that a body in motion will continue in its state until forcibly affected. That is, every moving body they observe in the world stops, seemingly by itself; so, how can they believe a physical law that appears to tell them otherwise?

Another problem posed by students' pre-existing mental models is that these often inform study practices; and, the students' approaches to learning physics upon entering university often consist of the "plug-and-chug" method of solving problems. That is, students rely on equations to find the answer without really about thinking about what the problem means, nor about the phenomena at large[26]. In order for students to correct their misconceptions, educators must present comprehensive replacements to students' existing mental models, as well as motivate them to adopt appropriate learning habits when studying the revolutionary ideas.

Mental models have certain underlying properties[27], irregardless of the subject matter to which they apply. First, they contain internal guidelines that define the scope and manifestation of their particular utility. Second, the models themselves can contain inconsistencies, internal contradictions and gaps. Third, the activation of a model may be independent of human determination - that is, people often are not aware of how to invoke the appropriate mental model to explain a given situation. Fourth, the ideas to which an individual's mental models pertain need not be distinct from each other; and, overlap of different models' perceived applicability can lead to confusion. Finally, models often act as a crutch for people, helping them to avoid critical thought and doubt concerning their understanding of the world.

Mental models in themselves are neither good nor bad; yet, incorrect ones will inevitably lead students astray. Students enter introductory physics courses with fully developed mental models; and, it is the role of the teacher to correct existing flaws, as well as to extend their scope and clarify their regions of applicability. Reddish outlines some principles for replacing existing mental models with better ones[28]. Students must clearly recognize a conflict between ideas presented to them and those they already hold. For example, motion on an air track or on a slick surface can convincingly demonstrate Newton's Law of Inertia, in a situation where friction is negligible. In this manner, students can realize the error in their preconceived ideas; and, once their erroneous mental models have been deconstructed, more accurate ones, such as those that incorporate Newton's Laws of Motion, can be constructed in replacement.

In the process of changing a students' mental models - that is, the process of teaching - consideration must be given to the way in which students' models interrelate with each other. Reddish describes a "mental ecology"[29], which governs how models are invoked, depending on external circumstances. The organization of a student's cognitive constructs should be considered, not only in the planning, but also in the delivery of a curriculum that follows principles cognitive studies.

One key to interacting effectively with students' mental ecologies is using appropriate language, which will access the proper mental model and not confuse the student by referencing several simultaneously. For instance, when common usages of terms like "friction," "heat" and "energy" do not refer to the strict scientific definitions, students can get confused[30]. A lecturer should try to only use appropriate, scientific language when discussing such concepts.

Another means of accessing mental models is to utilize a "story line" approach[31] when developing the curriculum of a course. Mental models are linked with each other, and students access or invoke them when external stimulus corresponds with remembered experience of previous cognitive interactions. Hence, a course should be structured such that the topics covered are linked, and such that the fundamental concepts are presented repeatedly in many different contexts. By emphasizing the links intrinsic to a physics curriculum, the subject matter appears more natural to students; moreover, it is more readily accepted, because it immediately suggests a structure for mental organization. By presenting topics as corresponding with recurring themes, manifested in a variety of situations, students are given a multitude of keys with which to access the mental models they will develop. Such a linked conceptual framework applies well to teaching many sweeping physical frameworks, like Newtonian mechanics, for example.

PER in the Classroom:

Following the principles of scientific methodology, through which well-founded theory, developed and tested through experimentation, inform improved practices, PER-guided innovations have been put into use to increase the learning potential of the lecture environment. The leading practitioners of PER have employed their developed techniques with reference both to teaching and to physics; and, through their work, several successful in-lecture teaching techniques have been refined. Although the ideal proportions of the techniques are difficult to attain, and though the perfect combination varies depending on the student, the main ingredients involved, outlined below, have each been shown to enhance elements of the learning process that occurs in lectures, as well as expand the learning environment of lectures to introduce new elements.

The goal of PER, as applied to lectures, is to transform the standard lecture into an active learning experience; that is, to supercede the type of interactions that a large, impersonal lecture typically allows, replacing them with the more engaging, more stimulating and generally more effective modes of interaction that derive from Dewey's apprenticeship model. Two techniques that strive towards this goal – to make lectures more exciting and more engaging – are Classroom Demonstrations and Peer Instruction. Furthermore, both of these methods have been successfully used in classes of over 1000 students[32].

Classroom Demonstrations:

Classroom Demonstrations allow the students a laboratory-like experience within the classroom, by facilitating hypothesis about, testing and observation of results pertaining to a physical phenomenon. To explain by example, one demonstration that has been used in PHY 138 involves the motion of a simple pendulum. A bowling ball is suspended from a cable that is secured to a solid frame, and the professor stands beside the apparatus with the ball held under her/his chin. The demonstration consists of releasing the ball, which swings in ordinary pendulum motion, and returns to the original position, without harming the professor.

The most apparent benefit of such a display is a "wow-factor," which, like the enthusiasm of the instructor, adds energy to the class and vibrancy to the material. Similar to demonstrations, computer animations and simulations can demonstrate physical phenomena, and both in a manner that appeals to students.

One problem with ordinary demonstrations, however, is that they are not particularly interactive, when simply enacted directly. Though they may impress the students, they may not directly be effective teaching tools. As Harrison points out, "although students love lecture demonstrations, often they don't actually learn from them"[33]. Formal studies on the effectiveness of non-interactive demonstrations corroborate this statement. One study, conducted by Eric Mazur (Harvard University) and his colleagues in 2004, concluded that "students who passively observe demonstrations understand the underlying concepts no better than students who do not see the demonstration at all."[34]

Nonetheless, the teaching effectiveness of classroom demonstrations can be enhanced by incorporating them with the Peer Instruction technique, as Harrison points out. By asking students to hypothesize about the outcome of an upcoming demonstration, and by asking them to explain their reasoning to their peers and come to a consensus regarding their predictions, students may learn more from demonstrations[35].

<u>Peer Instruction:</u>

Peer Instruction is an innovative technique that facilitates student engagement in the lecture material, while enabling a dynamic, evaluative dialogue between the students and the professor. This technique was devised largely by Mazur[36]. The initial requirement is a conceptual problem - Mazur terms these "ConcepTests."[37] The professor poses the problem to the class, and the students vote individually on the correct answer. Typically, the question is posed in multiple-choice format, and students can vote by raising their hands, using electronic clickers, or by similar means. If a significant fraction of the class is incorrect, the students break into small groups to discuss the possible solutions. (If most students know the correct answer at the start, the process terminates, with brief discussion by the professor. If most students answer incorrectly initially, the professor explains the concept in depth, rather than initiating peer discussions. Ideally, in each discussion group, students should have conflicting understandings, and at least one student should be correct.) Following discussion, the students vote again, and the professor may explain the problem and the correct solution. Class discussion can ensue, during which time, student interaction with the material is further heightened.

The key to Peer Instruction is evidenced by its name. The small-group discussions of students with their peers are where most of the learning takes place. The students are, essentially, left to work together to explain the problem presented. The underlying theory is that people are more receptive to new ideas, and are more likely to challenge their own preconceived notions, when working in intimate groups of their peers, rather than in larger, less personal circumstances. Furthermore, students are more likely to listen to explanations contradictory to their own understanding when presented by their peers, rather than by an authority.

The most important step, as aforementioned, is the discussion process, in which students try to reason through the problem and discover the correct answer, through discussion with their peers. Voting serves to inform the professor of the students' level of understanding. The early vote can determine whether the class needs to proceed with the presented problem - as explained, if most of the class understands the problem at the onset, the professor might conclude the activity with a few summary remarks. The later vote tells the professor about the success of the activity - if students still do not understand the concepts, more time should be spent on the topic, either in lecture or in tutorial. As with Classroom Demonstrations, Peer Instruction adds energy to the lecture environment, both through the discussion process and through voting, and it engages the students. However, the success of Peer Instruction is dependent on the original questions posed - if they are not challenging enough, or they fail to prompt discussion amongst the students, this technique will be of no use[38].

Tablet PC:

Classroom Demonstrations and Peer Instruction are useful to increase the effectiveness with which specific physics concepts can be taught in lectures. However, they take an extraneous position to standard lecturing, in part because of the effort involved in their execution (classroom demonstrations, especially, require extensive preparations), but more fundamentally, because they act to solidify accurate conceptions of topics that have already been introduced through more standard means. As already explained, the standard lecture introduces and contextualizes the subject matter; and, both functions are necessary aspects of the teaching/learning process. The standard lecture should not be eliminated altogether; nonetheless, PER and MER can both inform better techniques for lecturing itself.

A simple example of an innovation in actual lecturing, one which is especially relevant in the large-lecture setting, is the use of a Tablet PC. The downsides of lecturing with the aid of pre-prepared overheads, or with technology like PowerPoint, is that it is often difficult to match the pace and energy inherent in traditional use of a blackboard[39]. With pre-written lecture aids, the instructor can easily fall into the trap of teaching the material too quickly; moreover, presentation through such means minimizes the energy required by the lecturer. The Tablet PC, however, enables real-time writing, which can be projected towards large audiences, and which shows more effort on the part of the professor. Real-time presentation through the use of a Tablet PC can encourage students to ask questions (ie, the material is not already engraved in stone), and can also facilitate adjustment of lecture pace, depending on student understanding.

In very large lectures, ordinary blackboards are not an option, due to visibility constraints. Rather than resort to Powerpoint slides or other pre-prepared presentations, a Tablet PC allows the benefits of a blackboard, in addition to the visibility advantages of overhead projectors and/or television screens. Moreover, this medium allows easy incorporation of diagrams and animated simulations, which, as with Classroom Demonstrations, are very popular with students, and can illustrate phenomena effectively. The Tablet PC provides the convenience of a computer, along with the benefits of dynamic, real-time presentation of the lecture material.

<u>Representative Assemblies:</u>

The teachers' ability to affect student engagement in course material is not limited to the classroom. By empowering students to take ownership over their learning, which can be accomplished by allowing them input into the teaching process, students may be more motivated to exert good effort in their work. Moreover, with the empowerment allowed by input, the student will not feel resigned to the course structure, and may put thought into ways of improving teaching techniques, from her/his own perspective. Hence, a feedback mechanism, which relates to the course structure rather than to the content, may be a useful element of a physics course.

The Representative Assemblies (called “Student Management Teams”[40] in MER) are one such feedback mechanism, and are employed in PHY 138. The Assemblies are attended weekly by student volunteers and the course instructor. They are casual meetings, in which discussion is directed entirely towards course structure. Efforts are made to facilitate constructive discussion among students; more on the particulars of the Representative Assemblies in PHY 138 will follow later.

The message sent by course instructors to students in incorporating such a feedback mechanism is important. Simply providing a forum to hear student concerns and potentially make reactive improvements based on them clearly impresses upon students the realization that they are important to the course, and it helps them feel empowered in the learning process. Moreover, in lectures that employ many developmental PER-motivated techniques, student feedback can provide important qualitative evaluations of the benefits and drawbacks of particular innovations, as perceived by the students.

PER in Physics Tutorials:

Lillian McDermott at the University of Washington has worked extensively on developing teaching techniques for non-lecture components of physics courses. One of her group's main publications is *Tutorials in Introductory Physics* (2002), in which she develops a structure and curriculum for introductory-level physics tutorials. These "Activity-Based Tutorials" have been successfully implemented in PHY 138.

McDermott emphasizes that physics courses should aim to teach their students physical concepts and “scientific reasoning skills"[41], rather than quantitative calculation skills. Also, she addresses cognitive implications on student learning, and she designs these tutorials to "engage students actively in the construction of important concepts and in their application to the physical world"[42]; that is, they are geared towards helping students construct accurate, complete and accessible mental models to explain the physical concepts. McDermott appreciates the importance of utilizing instruction time effectively to facilitate "meaningful learning,"[43] part of which involves making students aware of their established mental models in order to motivate them to re-evaluate their prior conceptions.

McDermott's tutorials are structured via a four-part process, with evaluative and assessment measures incorporated. Each session begins with a pre-test, which helps both instructors and students to identify cognitive difficulties. The pre-tests also introduce the students to the learning expectations for each session. Students then work together in small groups on worksheets, which direct activities and present conceptual problems. Teaching Assistants do not give lectures, neither to introduce concepts, nor in answer to students' questions. Rather, they are trained to ask the students questions that will guide them along the proper cognitive path to the correct answer. This peer-based instruction methology, as in Mazur's techniques, serves both to create an active learning environment, as well as to disarm students, to allow them to more readily accept challenges to their preconceived ideas. The students are assigned homework, which "reinforce the ideas developed during the tutorial;"[44] and, at the end, a post-test is given to allow students and instructors to gauge what was learned and what requires more work.

PER in Laboratories:

The instructional laboratory is an integral component of any introductory physics course. From a scientific perspective, it introduces the experimental side of physics, along with teaching the proper methodology that must be employed in scientific investigation. In doing so, the laboratory serves three purposes: it teaches students basic laboratory skills, including error analysis; it evidences to students the labour involved in the development of physical theory; and it demonstrates to students the intrinsic uncertainty in scientific knowledge, highlighting that experimentation only corroborates or dismisses, but never ultimately proves, scientific theory.

There are many other, more pedagogically-oriented, benefits to the laboratory component of an introductory physics course. The most readily apparent of these relate to Dewey's apprenticeship model of teaching. A laboratory setting can establish a direct venue to engage students and provide them with memorable, interactive experience of physics concepts. However, student engagement in a physics laboratory is by no means ensured. There are many possible improvements that can derive from the application of PER principles to the physics laboratory.

A laboratory experiment should be customizable to the individual student's level of experience and pre-conceived understanding. One way to facilitate this is to allow for student choice in experimental procedures; for example, presenting a selection of optional sections, of which students can choose several for study, can help personalize the laboratory experiment. Along similar lines, providing a succession of levels to complete, and allowing students to pursue the experiment as far as they choose, could also help cater to students' predispositions. Likewise, encouraging creativity in approaching experimental problems, as facilitated by giving less direction in prescribed procedures, could help to engage students through a more active level of thinking. One example of this is a project that was given to PHY 138 students. The students were asked to measure the height of the main physics building at the university, and they were required to formulate their own procedure for doing so, given a selection of apparatus. Such a project requires analysis of the problem and its underlying physics, and it also forces students to take an active role in determining the solution.

The hands-on nature of the physics laboratory immediately prompts a higher level of student engagement than that of the standard physics lecture. An appreciation of students' individual learning styles allows maximization of this inherent potential for active involvement. Reddish treats this topic in his cognitive studies research. He emphasizes the importance of applying the "Individuality Principle"[45] in teaching physics, whereby the particular mental models and mental ecology of each student must be considered in teaching aims. As he explains, a student's mental individuality should be taken as the guiding framework of educational interaction with her/him, since this cognitive condition is the lens through which all information is interpreted. Moreover, Reddish categorizes different types of learning styles. He lists the manner in which a student prefers to obtain information (ie, by being told or by discovery), the nature of obtained information to which a student is most receptive (ie, abstract or concrete), and the student's preferred mode of presentation of information (ie, algebraic or graphical) as relevant learning styles to be considered. Learning styles are another aspect of cognitive theory that are relevant to physics instruction, and they can be particularly important in the laboratory setting.

Testing Techniques:

As stipulated initially, the purpose of PER is to increase the effectiveness of physics teaching practices. A natural question that arises, is how to accurately measure the effectiveness of a particular technique. Is student performance on conventional physics tests an appropriate rubric with which to evaluate unconventional methodologies? Moreover, PER aims to develop conceptual understanding of physics phenomena. Do conventional tests ask questions that require such an understanding? A significant amount of research has been done on testing, both in order to match the tests with the manner of instruction, and in order to ensure that the tests are assessing the proper proficiencies. Also, the purpose of testing has evolved from simply providing a quantitative assessment of students' proficiency relative to her/his peers, into a diagnostic and feedback tool to gauge student understanding. This effect, in turn, allows insight into the success of employed teaching techniques.

McDermott has worked on the development of accurate and appropriate testing procedures, and she incorporates her methodology into her teaching techniques, for evaluative purposes. As mentioned earlier, McDermott's tutorial framework utilizes pre- and post-testing, both to gauge the effectiveness of the worksheet activities and to inform students of the learning expectations of each tutorial session.

McDermott also prescribes an appropriate style for tests, in addition to describing a suitable structure via which they should be administered. She emphasizes that tests should be conceptual in nature, and should not be comprised of quantitative questions that require simple application of formulae[46]. McDermott stresses that "the ability of students to obtain correct answers for numerical problems often depends on memorized algorithms"[47]. This approach yields an inaccurate measure of a students "functional understanding"[48], and should be avoided. Instead, McDermott stipulates that “questions that require qualitative reasoning and verbal explanation are essential for assessing student learning”[49].

McDermott also clarifies how pre- and post-tests are to be structured relative to each other. To allow comparison of student performance on the two tests, they must test the same concepts, with the same level of difficulty. McDermott's research has found that similarity of the pre- and post-tests has very little effect on student performance.

Test development is a complicated science. A good technique for refining a test's questions and structure it to give it to a sample of students, to be critiqued. In her research, McDermott performs trial runs for test questions and also discusses them qualitatively with the students. The Representative Assemblies in PHY 138, for example, provide a forum for such student evaluation of potential tests and teaching techniques. The Representative Assemblies, as well as the other PER-motivated methods employed in PHY 138, will be studied in the following sections.

Physics for Life Sciences (PHY 138) at the University of Toronto

There is a strong drive towards the medical profession in our society today, and many students are striving towards higher education in the life sciences at universities across Canada. Most medical schools, as well as many other institutions of higher-education in health studies, require an introductory background in physics among applicants. The Physics for Life Sciences (PHY 138) course caters to students at the University of Toronto aiming towards medically or other biology or chemistry oriented professions, who require an introductory understanding of physics. The aforementioned propensity among students towards such fields of practice has rendered course enrollment in surplus of 1000 students. Also, the demanding schedule of the Life Sciences program prevents splitting the student body into multiple sections; hence, the entire group meets twice a week, each week for a year, in Convocation Hall, the largest auditorium at the university. Moreover, the challenges posed by the sheer size of the class are augmented by the fact that most of the students have no prior interest in physics, and have enrolled in the course for the purpose of fulfilling program requirements.

The PHY 138 course presents interesting, additional challenges to the already difficult enterprise of teaching introductory physics. Harrison and Pitre have been instrumental in facing these difficulties, and expanding the field of PER in the process. As a result, the PHY 138 course, despite its unique nature, provides an excellent setting for the study of PER in general. Moreover, the extraordinary aspects of the course facilitate evaluation of the durability of PER practices and the applicability of its concepts in extreme cases. In teaching, of course, each specific class is unique. The PHY 138 course is an exemplary starting point, from which embark upon a study of PER.

Teaching Methods in PHY 138

The Physics for Life Sciences course is a year long, introductory level course open to students in the Faculty of Arts and Science, who are not physics Specialists. Enrollment in the course is roughly 1000 students, the majority of whom are in their first year of university. The course is divided into four curricular terms, each one focusing on a different area of physics, and each taught by a different professor. A test is given at the end of each term on the material of that term, alone. Also, a cumulative final examination is given at the end of the year. The four test results, and the final exam grade, respectively, comprise the largest portions of the students' final grades. Laboratories, pre-class quizzes and web-administered assignments accumulate to the remaining portion. Refer to Appendix A for the Marking Scheme of PHY 138. Students meet twice a week for lectures, once weekly for tutorials and once biweekly for laboratories. Problem sets are administered weekly, via the internet-based infrastructure used in the course, and can be completed at the students' leisure. Refer to Appendix B for a complete description of the course structure, and to Appendix C for an outline of the curriculum. The textbook used is *Principles of Physics, A Calculus-Based Text*, by Raymond A. Serway and John W. Jewett Jr (Brooks/Cole, 2002, ISBN 0-534-49262-2).

A number of PER-guided teaching techniques have been used in the course. These innovations have been motivated by the same goals as drives PER in general. That is, course instructors strive to help each student develop an accurate, conceptual understanding of physics, rather hone her/his ability to solve quantitative problems. Practically, the teachers and coordinators aim to raise the level instruction and testing to reach a higher, more conceptual benchmark. Through the use of PER-developed innovations in teaching techniques, it is hoped that students will learn more and learn better. Student achievement on evaluations is hoped to represent these improvements.

Three elements of the PHY 138 course, which do not relate directly to PER, are Pre-Class Quizzes, In-Class Questions and written Homework Assignments. Students are required to answer quiz questions over the internet, prior to each week's lectures.

Questions are related to assigned readings, and are intended to prepare students for lecture material. In-Class Questions, similar to ConcepTests, are often posed to spark class discussion. These are also used to initiate Peer Instruction activities. Homework problems are assigned weekly, and submitted by the students to their Teaching Assistants for marking.

Two techniques employed in the lecture component of the course are Peer Instruction and Classroom Demonstrations, including Flash animations. Both of these lecture-based innovations were used predominantly while Harrison was instructing, during the first term of the course. Other professors employed these two techniques with varying frequencies; the effectiveness of these, as well as the non-lecture PER teaching methods, is evaluated based on first-term testing results, only. Also, a Tablet PC, and a microphone, are used during lectures. As aforementioned, these devices preserve the pace and energy of traditional blackboard instruction, while facilitating communication to a large number of students.

As discussed earlier, Peer Instruction increases the interactivity of the standard lecture, and it also provides feedback to the instructor as to the level of understanding of the students. Moreover, by facilitating interaction amongst students, it not only allows them to learn the concepts from their peers, but it also forces them to defend their opinions and re-evaluate their understanding. Peer instruction, in theory, couples the effectiveness of peer interaction with the demands of self-explanation.

In PHY 138, the biggest challenge to implementing Peer Instruction is facilitating communication between 1000 students and one professor. Coloured cards were distributed to each student at the start of the lecture, and during voting, these were used to signify the preferred option of the multiple choices. Harrison estimated the fraction of the class voting for each option, and he recorded the results.

Classroom Demonstrations incorporate an exciting, observational element into the standard lecture. In doing so, this technique is intended to increase the energy, enthusiasm and involvement of the student body. Moreover, by using demonstrations that have a "wow-factor," like that of the bowling-ball pendulum mentioned earlier, the class becomes generally more enjoyable for all involved. In PHY138, Classroom Demonstrations were performed by Harrison several times, to teach a variety of concepts.

Outside of lectures, two main PER developments have been incorporated into PHY 138. The foremost of these are the McDermott tutorials. Teaching Assistants are specifically selected and trained to administer these activity-based tutorial sessions, and the McDermott publication, *Tutorials in Introductory Physics* (McDermott, 2002), is used, with minor adjustments. Students were divided into groups of roughly 25 per tutorial; there are 41 meeting sections in total, and each met weekly, either on Wednesday, Thursday or Friday.

In addition to the McDermott tutorials, one other non-lecture innovation was utilized in PHY 138. Representative Assemblies allowed students to enter into constructive dialogue with the course instructor, on topics relating to content delivery, overall course structure and the benefits and drawbacks of the specific components used in the course. The Assemblies met every Friday for an informal lunch, attended by the professor and one representative from each tutorial section. (To keep the group size small, the tutorial sections rotated, such that representatives from the Wednesday sections met one week, those from Thursday met the next week, etc.) Lunch was provided to the students – this added to the casual atmosphere, as well as increased attendance – and time was allotted for private discussion amongst the students, before the professor joined the discussion. Invariably, students feel inhibited in the presence of the professor; hence, reserved time for private discussion is essential to receiving meaningful, honest feedback from these Assemblies.

One other component of the PHY 138 course is the Mastering Physics internet package, which was introduced this year. Students are given weekly problem sets, to be completed online, and performance is tracked to provide feedback to course instructors. More information on the software can be found at http://www.masteringphysics.com/.

Computer-aided teaching has increased in use exponentially in recent years, and there are currently a multitude of avenues through which computer and internet technologies are being used for educational purposes. In fact, computer learning encompasses its own field of study; and, though the intersection with PER is extensive, the field of instructional technologies is deemed outside the scope of this study. One centre for the study of instructional technologies is Michael Barnett's group at the Lynch School of Education at Boston College.

Feedback from the Representative Assemblies

At the initial three Representative Assemblies (that is, the initial meeting for each of the Wednesday, Thursday and Friday groups of tutorial sessions), Harrison outlined the intended structure for these meetings. The purpose of the Assemblies, as he described, was to discuss the effectiveness of the overall learning environment in PHY 138. He suggested possible discussion topics, all of which related to lecture methods, including use of the Tablet PC, lighting and sound levels, lecture pace and visibility of the projection screens. This information was presented after personal introductions, and following these proceedings, Harrison left the room, to allow the students to coalesce their comments, via discussion in small groups.

The Representative Assemblies facilitate feedback to the course instructors regarding the perceived effectiveness of the teaching techniques used. Some recurring themes in the discussions will be identified, shortly. The Assemblies also allow the instructors to gear evaluative measures towards the students, in order to design these to give more effective feedback when used. For example, in the October 15 Assembly (with the Wednesday tutorial groups), Harrison distributed a course evaluation survey and asked students to critique the wording. This survey was later used to assess students' impressions of the PER-based techniques used; and, the results from this survey will be discussed later in this report. Finally, the Representative Assemblies have a more subtle effect, in that they allow the student body to feel control over their learning environment. The Assemblies allow student representatives to voice concerns and make suggestions, and as a result, students are empowered to take charge over their learning and exert the effort to make the course experience more beneficial to them. As Harrison stated to the October 1, Thursday group, Assembly, quoting Priscilla Laws at Dickinson College: "If you don't test for it, you don't get it."[50] Similarly, if students are not given an opportunity to make a difference in their learning environment, they are unlikely to take steps to do so.

The following is a description of the most common issues raised by students at the Representative Assemblies. These results are based on the observation of the first five Assemblies (two sessions of the Wednesday groups, two of the Thursday groups and one of the Friday groups), spanning the first five weeks of the course (ie, the first term, taught by Harrison). Although other issues were presented over this time, the following points were reiterated several times, throughout the five weeks of observation. Also, although the following comments are all complaints, the Assemblies provided a lot of positive support for the techniques used. The Assemblies were designed, as mentioned, as a means of directing improvement of the course; and, the comments that follow reflect that objective.

- *Lecture material should relate more closely to pre-class quiz questions.*

  This comment highlights the difference between the lecture material and the textbook content. The pre-class quizzes are designed to reflect the textbook material, in the attempt to influence students to read the relevant chapters of the course text prior to lecture. The PER-based lecture techniques, and standard lecture techniques in general, are thought to be more effective when students have seen the material before. This allows more critical thought to occur in lectures, and students can be more actively engaged in challenging their preconceptions of the subject matter. Correspondingly, the lecture material reaches beyond the scope of the textbook, and treats the studied phenomena from a more conceptual and a more holistic perspective. While the students may find it inconvenient to be presented with seemingly different material in lecture than they had read previously in the textbook, this dual approach strives to emphasize the underlying concepts common to both.

- *More physical examples should be discussed in lectures.*

  This comment reflects the theoretical nature of the lecture material. As intended by PER, the lectures in this course challenge students on a conceptual level; additionally, little emphasis is placed on honing problem solving skills. Physical examples are important, however, as they relate to students' mental models governing their observation of everyday physical phenomena, and as they also interrelate theoretical and experimental physics. In PHY 138, Classroom Demonstrations, as well as In-Class Questions and Peer Instruction, aim to engage students on an observational level, providing stimulus to their mental models and illustrating theoretical concepts in practice.

- *The Mastering Physics interface is frustrating to use.*

  The students' main objection voiced against the MP package is the strict syntax that must be adhered to when inputting solutions to problems. Students complained that their answers were marked as incorrect due to misplacement of brackets, or other trivialities. Nonetheless, proper form is important, and the MP software is extremely useful for administering quizzes to a mass number of students.

  In this case, however, the issue may indicate a problem with the Representative Assemblies, rather than with the MP software. The student survey, of which the results will be discussed shortly, indicates an overall positive impression of the MP software. The effectiveness of the Representative Assemblies at actually representing the opinions of the class as a whole may not, as evidenced here, be taken for granted.

The Representative Assemblies facilitate discussion between the instructor and the students on course-related issues. However, questions have often been raised in the Assemblies themselves, often in the absence of the instructor, as to how representative they actually are. One problem may be a lack of dialogue between the student representatives and their tutorial groups – it may be beneficially to allot a few minutes, every three weeks prior to an Assembly, for students in the tutorials to indicate their concerns to their representatives. Also, it may even prove effective for the representatives to meet with Teaching Assistants, with whom they are familiar, rather than with the instructors themselves, with whom the students may have had little or no direct contact.

The Representative Assemblies have proven effective as a mechanism for bridging certain gaps between instructors and students, as exemplified by students' critique of the class survey. Also, the Assemblies inform the instructor about the impressions that students have of the course. However, as shown by the misdirection of the preceding comments, the Assemblies may not be entirely functional, in their current setup, as a constructive mechanism for course improvement.

Fall and Spring Survey Results

A questionnaire, which was developed, in part, through critiquing by a Representative Assembly, was given to students in lectures during the sixth week of classes (October 20 - 22). Students were asked to evaluate how effective a learning tool each of the instructional techniques used in PHY 138 was for them. Also, the final question asked students to compare the use of the Tablet PC in this course with that of Microsoft PowerPoint, used in other courses, with which they would likely be familiar. This section examines the results of the survey. The survey was repeated in the final term, during the twenty-first week of classes (March 9-11).

Questioning was done via a 7-point Likert scale. Eight questions regarding PER-based instructional techniques, plus one other question regarding the Tablet PC, were asked. Refer to Appendix D for a transcript of the survey. Approximately two thirds of the class responded, which translates to a sample population of over 600 students. Students generally responded positively, regarding their impressions of the effectiveness of the teaching techniques. As McDermott emphasizes, “the primary criterion for the effectiveness of instruction must be the assessment of student learning”[51]. Hence, these results are used here simply to gauge how students feel about the PER-based techniques used, rather than as a measure of the effectiveness of these practices.

In the Fall survey, the most effective techniques, as judged by the students, were In-Class Questions, Interactive Demonstrations and Flash Animations. Each of these received positive responses by over 70% of the sample population (ie, by over 560 students). Also favoured among students were the MP Problem Sets and the Written Homework assignments, which both received over 55% positive responses (ie, over 440 students). None of the techniques received a majority of negative responses. Peer Instruction (called “Small Group Discussion” on the survey) and the online Pre-Class Quizzes received a majority of neutral responses, at 58% and 53%, respectively. The question of preference of Tablet PC over PowerPoint also received an overall neutral response, with a roughly even distribution among other choices on the scale.

Of interest in the above results is the response to the MP Problem Sets, as mentioned earlier. While students in the Representative Assemblies were opposed to this mechanism, the majority of students considered them to be useful learning tools. (It should be noted that some problems from MP were used verbatim in tests, which may have factored into this result. Such use of these problems ensured that students had completed the problem sets themselves, rather than copied the solutions.) The large positive majority for Demonstrations and Flash Animations is also interesting. Both techniques are designed, in part, to engage the students and add energy to the lectures. This result may indicate success in these aims.

For the survey in March, far fewer students – roughly one third as opposed to two thirds in October – answered the questions. The results were not drastically different, save a few exceptions. The In-Class Questions and the Flash Animations were still deemed effective, scoring positive responses of 69% and 79% respectively. The Demonstrations had dropped in student opinion to an overall neutral response by 62% of the sample population. The MP Problem Sets and the Written Homework both received better responses than earlier, with 75% and 66% of the sample population, respectively, choosing positively. The response for Pre-Class Quizzes had not changed significantly; however, Peer Instruction received an overall negative response, with 53% of students not favouring this technique. The McDermott Tutorials were not used in the fourth term, as the tutorial activities did not exist for the subject matter covered. Finally, comparison of the Tablet PC vs PowerPoint as an effective presentation tool swayed in favour of the Tablet PC; and, results of this survey were 65% positive for this question. Refer to Appendix E for a complete, comparative presentation of both surveys' results.

The student response to Peer Instruction is surprising, and Harrison addresses it in is summary of the survey statistics. As he indicates, Peer Instruction discussions focused on the In-Class Questions, and these were often standard, conceptual questions that were not formulated specifically for this class[52]. Harrison relates how students generally performed better on these questions than had students in other universities; hence, Peer

Instruction sessions were often less eventful, and were possibly less effective. Harrison clarifies, though, that from the Instructors' perspectives, Peer Instruction did, at times, seem very effective at teaching difficult concepts.

A final point also pertains to the relation between the survey and the Representative Assemblies. The Assemblies were used to guide the development of the survey; however, the relationship can be symbiotic. The results from such surveys can be used to guide future discussion in the Assemblies, to more clearly resolve students' impressions and the perspectives that inform these opinions. Together, student surveys and Representative Assemblies could be a powerful, constructive feedback mechanism.

Term Test Results from Mechanics Unit

On the October term test on the Mechanics unit of PHY 138, a question from the previous year's term test was repeated, with slight modification, in order to perform a cursory assessment of the effectiveness of the techniques employed this year. The question on the test in October 2003 is as follows:

A wheel of radius R rotates about a fixed axis. When a point at a distance R from the center is moving with angular speed ω, a point located at a distance R/2 from the center is moving at angular speed _____.

a. $\omega/4$ b. ω
c. 2ω d. $\omega/3$
e. $\omega/2$

Figure 1 - Rotational Motion Question on First Term Test, in October 2003

The correct answer is option b; and, 49% of 1076 students answered this question correctly. On the term test this year, in October 2004, the question was as follows:

A disc of radius 2R rotates about a fixed axis. A point at a distance R/2 from the axis has an angular speed of ω. What is the angular speed of a point a distance R from the axis of rotation?

a. $\omega/4$ b. 2ω
c. $\omega/2$ d. ω
e. 4ω

Figure 2 - Rotational Motion Question on First Term Test, in October 2004

On this test, the correct answer is option d; and, 89% of 963 students answered correctly. At first glance, these results seem to indicate dramatic success of the new teaching methods. Apparently, forty percent more students learned the basic concept of rotational motion in this year, compared with last year's class. However, the results cannot necessarily be taken at face value, because this year's students had access to last year's test, with the above question on it (Figure 1).

This factor introduces several possibilities for complicating the results. For one possibility, students could have remembered the question verbatim, and, without understanding the underlying concepts, picked the same answer for angular speed, ω, as they had seen previously. Another complication is that students could have seen the question on the previous test and deliberately focused on the concept of rotational motion when studying, as a result. However, it is also possible that students who remembered the question in Figure 1, while studying for this year's test, would have been confused by the slight differences and chosen the incorrect option. Finally, it is not known whether students who wrote the test in October 2003 had access to previous years' tests, on which similar questions were asked. Despite these complications, however, the improvement from 49% correct responses to 89% over one year is very impressive.

Summary of Slavin's Survey of Physics Instruction at Canadian Universities

This section addresses the recent survey published by Alan Slavin, of Trent University, regarding the methods used to teach introductory physics at several Canadian Universities. Slavin begins with an article addressing the motivation for PER and some major developments over the past 30 years. He discusses a variety of teaching techniques, and he also describes the Gain coefficient, developed by Hake, which is widely used in evaluation of student learning. He summarizes methods used at Trent University, and then tabulates methods used at other universities.

Slavin's work focuses on the large lecture setting, and analyzes techniques employed therein to teach physics more effectively. To provide a meaningful comparison with the class size of PHY 138, only the largest of the listed universities are considered. Of the 12 schools surveyed, the largest, in terms of student body and reputation, are Concordia, McGill and McMaster (and Toronto). The teaching methods used at these schools, as listed in Slavin's report, are shown below. Those used at Toronto are also included, for reference:

Interactive Teaching in Canadian Universities					
University	**Year level**	**Course material**	**Interactive methods**	**% of "lecture"**	**Contact**
Concordia	1 Gen. ed. 1 1	Mechanics, waves& modern physics Origins of universe Mechanics, E&M Waves & modern physics	Reflective write-pair-share Peer Instruction Reflective/ concept writing	60 100 15 50	C. Kalman B. Frank B. Frank S. Misra
McGill	1 2 1	Mechanics, waves Musical acoustics E&M	Peer Instruction. Modified PBL Peer Instruction.	80 60 80	R. Harris R. Harris M. Knutt
McMaster	1	Mechanics, E&M, waves	Peer Instruction, Interactive tutorials	30	K. Sills

Toronto	1 1	Mechanics Mechanics, waves, E&M, relativity, quantum physics.	Peer Instruction, JITT, Worksheet tutorials.	35	D. Harrison S. Morris

Table 1 - Slavin's Survey of Interactive Teaching in Canadian Universities, Abridged

A number of the Interactive Methods listed in the above table have not been mentioned previously in this report, and some are known by alternate names. For clarity, those not previously discussed are now defined. Reflective write-pair-share is an interesting technique that requires students to explain, in words, their conceptual understanding, and then critique what they have written. It involves pre-class writing in reflection on assigned readings, followed by in-class discussion among students with conflicting interpretations. Later, an individual critique is assigned or completed in class. Reflective/concept writing involves similar verbal descriptions of physics concepts, and culminates in an essay question on the final examination.

PBL stands for Problem-Based-Learning, and at McGill University, the physics course almost entirely follows this approach. The curriculum is comprised of a variety of physical scenarios, chosen by the instructor for relevance to the students and applicability to the subject matter. Students work in groups to answer structured questions pertaining to the phenomena under study.

Finally, the JITT method, employed in Toronto, stands for Just-In-Time-Teaching, and refers to the pre-class quizzes administered over the internet. As described by Slavin, the testing "spurs students to do assigned readings, and provides the instructor with feedback on student difficulties."[53] Moreover, the use of pre-class quizzes in conjunction with Peer Instruction allows critical analysis of the concepts presented in the readings and lecture, and helps students formulate accurate mental models to explain these phenomena.

For each of the above-listed schools, it is important to consider the methods as working in conjunction with each other, as is the case with the pre-class quizzes leading into in-lecture Peer Instruction in PHY 138. As expressed in Reddish's idea of a story line approach to teaching physics, each element of a physics course interrelates with each other in defining the overall learning experience. In the remaining sections of this report, PER principles are applied to the laboratory component of PHY 138, in the attempt to more closely integrate it with the lecture and tutorial components of the course. To this end, a laboratory activity is designed and performed by students, and its effectiveness at enhancing their conceptual understanding of physics is measured.

PER Principles Applied to the Introductory Physics Laboratory

An integral component of any introductory physics course is the instructional laboratory, in which students gain an appreciation of experimental physics and learn proper techniques for its practice. As discussed earlier, in reference to Dewey's apprenticeship model of teaching science, which is explained in regards to Reddish's clarification of cognitive factors in learning, the laboratory provides a venue for interactive, hands-on observation of the phenomena under study. Moreover, students learn valuable experimental skills, as well as develop an understanding of measurement uncertainty and of the process by which accepted theoretical knowledge is developed.

Any PER-based modification to standard introductory physics laboratories should not detract from the existing educational benefits present. Specifically, innovations in the laboratory should not hinder learning experimentation techniques, should not prevent utilizing methods of accounting for uncertainties, and should not restrict observation of practical manifestations of physical theory. Rather, PER-based modifications must improve the students' learning experience in the laboratory, and PER-guided evaluation measures must be used to assess resultant effects and determine what benefits were achieved.

In order to make educated hypotheses of possible approaches for improving the standard introductory physics laboratory, one must return to the guiding principles of PER. Through formal education, students should develop an accurate, conceptual understanding of physics concepts, and in such educational courses, evaluations should test this comprehension. Additionally, students enter the classroom, or laboratory, with preconceived mental models of how the world works; furthermore, these mental models are often erroneous. Teaching an accurate understanding of physics involves accessing and challenging students' pre-existing mental models, and presenting convincing, comprehensive alternatives to replace inaccuracies and fill in cognitive gaps. Moreover, students are typically receptive to such cognitive redefinition when they are learning from their peers, and when the subject matter is relevant in their daily experiences.

A four-part approach is proposed for the application of PER principles to the standard laboratory. Firstly, peer interaction will be facilitated by having students perform experiments and submit informal reports in pairs. (Students are already paired in the standard laboratories of PHY 138; and, the effects of this approach will not be tested explicitly.) Also, a personal environment will be created by having five pairs of students work on the same experiment (on five different sets of apparatus), in one room, guided by one Teaching Assistant. A friendly atmosphere could encourage students to interact with each other; and, hence, learn with one another.

The second proposed modification to the standard introductory physics laboratory involves the topics selected for experiments. The story-line approach to teaching physics, described by Reddish, will be adopted in order to relate classroom concepts with experimental procedure. If laboratory experiments demonstrate and expand upon topics presented in class, it is hoped that students will gain a better understanding both of the concepts and of the interrelation of theoretical and experimental physics.

In conjunction with a story-line approach in teaching, evaluation of laboratory performance must assess students' development of conceptual understanding of and experimental proficiency with the subject matter. The development of conceptual understanding can be evaluated through testing, conducted before and after the laboratory activities (ie, pre- and post-tests). Also, if the story-line approach is successful, it should be assumed that students' performance on regular course evaluations, pertaining to the specific topics addressed, will also be affected. Hence, test questions could be designed, which focus on students' understanding of concepts re-iterated in laboratory experiments. The development of experimental skills can be evaluated through students' reports, either formal (ie, a typed, scientific-paper style report) or informal (ie, a written overview of the procedure, results, analysis, etc). Correspondingly, students should be explicitly challenged by assigned activities to develop and use proper experimental technique and analysis skills. For example, by asking students to show the existence of a theoretical, mathematical relationship in observed data, or by requiring them to analyze errors in more complicated cases than those explicitly taught, students' are challenged to use and possibly reconsider their understanding of experimental principles.

Another potential way to access students' mental models concerning physical phenomena involves introducing a context to standard laboratory experiments, one to which students can relate through everyday experience. For instance, an introductory laboratory studying DC circuits, using a multimeter, protoboard and other electrical apparatus, should be given an additional context. The circuit could power a light bulb, or it could represent a thermostat control. Through this approach, although the experiment remains unchanged and the procedure is unaltered, students are no longer working with a circuit on a protoboard; rather, they are studying the light in their bedroom, or learning how the thermostat in their home keeps them warm in the winter. The idea is to reconstitute students' preconceived mental models of phenomena in the world around them, through the study of real-world physics. The hope is that this will help students apply theoretical principles studied in the classroom to the physics with which they interact on a daily basis. Such an integration of theoretical principles into deep-rooted understanding of the world can be assessed through conceptual tests, as well as the use of real-life examples in examination questions.

The RC Circuits Laboratory

The laboratory experiment developed in this project was aimed towards teaching the physics of a capacitor and the function that derives from it in a simple resistor-capacitor (RC) circuit. This topic is covered in the third term of PHY 138; and, the capacitor is a device with which first-year students of the Life Sciences are typically unfamiliar, initially. Knowledge of capacitor theory and function is relevant, in general because of the prevalence of the device in everyday circuits, and specifically in the Life Sciences, because of its utility in modeling processes, such as molecular transfer across biological membranes. The capacitor is a basic electrical device, and it is important that students in the sciences understand its underlying physics and the uses that derive from its theory.

The experiment was motivated by the aforementioned principles of PER in the introductory physics laboratory. Two procedures were developed - both of which studied the same capacitor circuit, but from two different approaches - and through them, the effects of two of the aforementioned principles were explicitly studied. Furthermore, design of the laboratories was influenced by the structure of the introductory physics laboratory in PHY 138, which already incorporated one of the PER principles discussed in the previous section. In both cases, conceptual testing methods, as described earlier, were employed in the evaluation of student performance and learning.

The laboratory component of PHY 138 follows a peer-learning model, in which students work in pairs to complete a guided experimental procedure and submit an informal (ie, hand-written) report of their work. For both procedures of the developed RC circuits experiment, the peer-learning approach was maintained. Five pairs of students, each pair working on a separate apparatus, proceeded through a set of preliminary exercises, after which they completed a set of measurements using the apparatus. The final measurements required were the same in each of the two procedures; the only differences were the specifics of the apparatus, and the preliminary exercises that instructed the students on how to use the apparatus.

The first PER principle tested through the developed, RC circuits experiment was the story-line approach to introductory laboratories, which was adapted from Reddish's original idea. Simply stated, the topic of the laboratory matched explicitly to one covered theoretically in the classroom. Students are first introduced to capacitors in PHY 138 in the third term of the course[54], which focuses on Electricity & Magnetism. Students learn about the energy in capacitors when learning about electric potential. The main RC circuits instruction follows, during which they learn the temporal current and voltage behaviour of an RC circuit, as derived from Kirchoff's Laws. In the lectures of PHY 138, RC circuits serve to exemplify Kirchoff's Laws and introduce basic circuit analysis. In the laboratory, the RC circuits experiment strives to present a tangible, interactive application of the theory, in correspondence to the story line approach for introductory physics laboratory. Since both developed procedures follow this principle, overall student performance in regular course testing, comparing students who performed either procedure with those who did not perform this experiment at all, will be used to assess the effectiveness of this approach.

The difference between the two procedures is the underlying context expressed through each. The "standard" procedure does not incorporate any external context; hence, it acts as a control, to be used as a comparison when assessing student learning. The "contextualized" procedure uses sound to facilitate observation of the capacitor function. That is, the apparatus consists of an RC circuit, connected to an integrated circuit chip that functions as a timer. The timer outputs a square wave electrical signal, the frequency of which is determined by the time constant of the RC circuit. The resistance of the circuit is fixed, and the student connects a capacitor, to set the frequency of the output signal. In the "standard" procedure, the output signal is observed on an oscilloscope, and students collect frequency vs capacitance data, which is analyzed according to the theory they have been taught. In the "contextualized" procedure, the output signal is connected to a speaker, and its frequency is determined by the observation of sound wave interference (ie, beats) with sound produced by another speaker connected to a frequency generator. Students adjust the generator's frequency until beats are observed, and record the setting at which the phenomenon occurs. Students are required to collect the same data as in the "standard" procedure, as well as to analyze it according to the same criteria.

Both procedures aim to deliver the same educational benefits inherent to normal physics laboratories. Both demand proper experimentation techniques to be practiced by the students; regarding experimental appartus introduced, the "standard" procedure uses an oscilloscope, and the "contextualized" procedure uses a frquency generator. Additionally, both require extensive, conceptual error analysis. Students must estimate the uncertainty of the frequency measurement of the output signal. (In the "standard" procedure, students are instructed to count the peaks on the oscilloscope trace, which introduces uncertainty. In the "contextualized" procedure, the main uncertainty in the frequency measurement is the bandwidth over which beats can be heard.) Furthermore, typical techniques for treatment and propagation of errors are necessitated by the analysis required, for which students must graph their results, determine the capacitance of an unlabeled capacitor by interpolation from this graph, and also calculate the constant resistance of the apparatus. Finally, both the "standard" and the "contextualized" procedure facilitate observation of physical phenomena, and require comparative evaluation of the experimental observations relative to theoretical predictions.

The final PER principle addressed by this experiment is that of conceptual testing. In both procedures, students are each given a pre-test and post-test (the tests are identical between the two procedures), which ask four, conceptual, multiple-choice questions pertaining to capacitors and the function they enable in an RC circuit. Furthermore, students are required to interpret their results conceptually, both verbally, through discussion of the relationship between the capacitor used and the output frequency, and analytically, by using their data to determine unknown quantities.

Aim of the "Contextualized" Procedure

One application of PER principles to the introductory laboratory setting gives rise to the idea that the laboratory experiment should relate to the students' everyday experience, in order to facilitate cognitive connection between experimental observation and daily life. Students form mental models to explain the phenomena in the world around them, and these explanations govern their understanding of the physical world. In order to affect how they understand the world, and in order to impress more accurate alternatives to those preconceived, laboratory experiments should bear some immediate resemblance to everyday phenomena. As aforementioned, this can be accomplished via an underlying context, which should be implemented in a manner that does not fundamentally change the physics being studied.

The "contextualized" procedure for the RC Circuits laboratory aims to provide such a relevant context, through which students can relate the physics under study to aspects of their everyday experience. The output signal of the apparatus is observed through sound; moreover, the frequencies produced are in the octaves of typical auditory experience. It is postulated that students will hear the sounds from their apparatus, and might recall instances in their ordinary experience when they heard similar sounds. As they learn the governing physics, they may be accessing other mental models that pertain to sound, and may be developing links between RC circuits and frequency and sound.

It is not assumed that the context of the laboratory will directly inform the development of mental models pertain to the actual physics observed. Rather, it is hypothesized that the conceptions developed through experimentation will be more closely linked with other physical understanding, through the context. Moreover, the aim is to connect the understanding of the observed phenomena with daily understanding, such that students will access and re-assess their conception of RC circuits in non-academic settings. For example, when students later hear similar sounds in the outside world, they may recall their experiment, and consider the implications of what they observed. Or, they may hear a sound and think of the capacitance required to produce it -

a large capacitance would result in a long time constant, which would produce a low frequency, and vice versa. Either way, it is thought that the more intrinsic a students' understanding of physics is in their everyday lives, the more thoroughly they will understand the physics, and appreciate its connections to other phenomena experienced.

In order for the underlying context of a laboratory to influence performance on a theoretical test, that is, in order for experimental observation to affect test scores, the actual topic of the laboratory should correspond with an element in the lecture curriculum. In this case, both the "standard" and the "contextualized" procedures ascribe to a topic explicitly covered in lectures. Hence, it is postulated that any connections formed between everyday experience and laboratory observation, potentially facilitated by the underlying context of the procedure, will be reflected in test scores. Hypothetically, students will learn the material through lecture and other theoretical study, and gain hands-on experience pertaining to the topics in the laboratory. Moreover, the context of the laboratory will present relations to everyday experience, so their observations will translate into a more integrated understanding of the experimental physics. Since the laboratory concepts are the same as those presented in lecture, students will, in theory, develop a more complete, integrated understanding of the theoretical concepts being taught.

Laboratory Logistics in PHY 138

The laboratory component of the PHY 138 course runs throughout the four terms of lecture. Students work on the experiments in pairs, with the aid of laboratory guides and with the assistance of Teaching Assistants. Students have one, three-hour time slot per experiment (with the exception of certain experiments that may be extended over multiple time slots), and they submit one informal report per pair, one week following experimentation. Students complete, on average, one experiment on a biweekly basis. Experiments during the first two terms of the course are mandatory; whereas, students are allowed choice of their experiments in the later two terms. Furthermore, students submit, individually, one formal report per term, which constitutes 20% of their laboratory grade. Overall, the laboratory grade comprises 20% of the overall course mark. Refer to Appendix F for the composition of the laboratory grade.

The aim of the laboratory in PHY 138 is significantly different that of the RC Circuits experiment developed, even with regards to the "standard" procedure. The PHY 138 course homepage describes the purpose of the laboratory component as follows:

> *By convention, Physics is divided into theoretical Physics and experimental Physics. You will learn about the latter in the laboratory, which will acquaint you with the techniques and limitations of measurements; the lectures and tutorials are primarily concerned with theoretical Physics. As a consequence, the lab makes no attempt to relate to lecture material, although you will discover that in the second term you may choose experiments connected to lecture topics if you wish.*
>
> \- PHY 138 Course Outline

Hence, it is expected that comparison of term test results between students who performed the RC Circuits experiment and those who did not should describe the effectiveness of the experiment at teaching the concepts studied.

The RC Circuits experiment ran through the third term of PHY 138, during study of RC circuits. Students volunteered, in their pre-assigned pairs, to perform the experiment, and ten students (five pairs) participated in each session. Four sessions of the experiment ran, two of the "standard" procedure and two of the "contextualized" procedure. Furthermore, one session of each procedure ran before RC circuits were taught in lecture, and one session of each ran after the lectures on the material. The author of this report supervised the sessions, as a Teaching Assistant would, and efforts were made by him to ensure that the sessions ran in the same manner, and that they also ran in a manner similar to that of the ordinary PHY 138 laboratory experiments.

As with the ordinary PHY 138 laboratories, students submitted an informal report, one per pair, one week after performing the experiment. The reports were marked by the author of this report; and, observations from students' report inform some qualitative assessment of the effectiveness of the two procedures, and of the experiment in general. Upon request, students were permitted to write their formal reports on this experiment. An additional 5% was added to students' informal report grades, in appreciation of their participation in this study.

Laboratory Guides for the RC Circuits Experiment

Two laboratory guides were written, one for each of the procedures, to aid and direct students performing the RC Circuits experiment. These guides were editted and approved by Harrison and Pitre, prior to the first laboratory session. Refer to Appendix G for guide of the "standard" procedure, and to Appendix H for the guide of the "contextualized" procedure. Note, repeated sections have been omitted from Appendix H.

The two guides differ only in the Preliminary Exercises, which instruct the students in using the apparatus, via step-by-step directions as to how to observe the output signal of the circuit. The guides are divided into seven main sections: Objectives, Introduction, Background, Apparatus Function, Apparatus Setup, Preliminary Exercises and Procedure. Students are presented with the theory of resistors and capacitors, the behaviour of an RC circuit and the operation of the circuit in the apparatus, which includes an integrated circuit timer chip. The Apparatus Setup instructs students how to connect the various devices, and the Preliminary Exercises, as mentioned, familiarizes students with the apparatus, as well as highlights sources of error in the observations. (As mentioned previously, the measurement uncertainties derive from different things in the two procedures; however, both sources are significant, and both require recognition, explanation and proper analysis.) The procedure section asks students to collect frequency vs capacitance data for the output signal of their apparatus, and requires analysis of this data and use of it to determine two unknown quantities (the capacitance of an unlabelled capacitor and the resistance of the circuit apparatus). Rather than giving step-by-step instructions, it states the requirements, and asks suggestive questions to highlight important considerations. This follows the approach of the McDermott tutorials, as described earlier.

In writing the laboratory guides, care was taken to use appropriate language, which would be understood by students and which did not make irrelevant, non-scientific references. Laboratory guides of other PHY 138 experiments were used as examples for language and structure.

Students' learning styles were also taken into account when writing the guides. As described by Reddish, different students learn differently[55], and teachers must aim to cater to these learning styles in order to reach students effectively. The explanations of concepts relevant to the experiment were presented in a variety of forms, both textually, graphically and through equations. For example, resistance and capacitance were described in words, and equations were presented to describe Ohm's Law and capacitor voltage. Circuit diagrams illustrated charge and discharge cycles of an RC circuit, and graphs depicted the respective exponential relationships of the voltage across the capacitor. Additionally, the equations for these relationships were given, though they were not derived.

Moreover, the Preliminary Exercises and Procedure of the experiment allowed different modes of working, in reference to different learning styles. Students were asked to describe the relationships, graph the data, and analyze the theoretical equations, allowing them to work in their preferred style, as well as challenging them to think in other modes.

The laboratory guides were designed to present the information necessary to performing the experiment. In doing so, they necessarily presented the theoretical perspective, to be compared with experimental observation. Hence, the students who performed this laboratory would have had an advantage over their peers in terms of the term test, as they had more exposure to the theoretical content. This will be discussed further when assessing the teaching effectiveness of the procedures.

Pre- and Post-Tests for the RC Circuits Experiment

Corresponding with the PER principle of conceptual testing, the pre- and post-tests in the RC Circuits experiment aimed to gauge the students' understanding of the subject matter prior to performing the experiment and what they learned from the experiment, and also to inform the students of the learning expectations involved. As mentioned earlier, the effectiveness of any test as an evaluative measure of conceptual understanding depends both on the questions asked and on the manner in which they are presented. The theory behind the pre/post test given for this experiment is discussed briefly below, followed by an explanation of each question. (Note that the questions on the pre-test and post-test were identical, only the order was changed.)

The test was comprised of four multiple choice questions. Although Dr. McDermott advises against the use of multiple choice questions in tests[56], citing that short-answer explanations are a better judge of conceptual understanding, the multiple choice format was used to avoid possible subjectivity in marking. Moreover, the use of identical questions on the pre-test and post-test is not thought to affect the results. As Dr. McDermott states, "research has shown that prior experience with a pretest has virtually no effect on student performance on a post-test."[57] The order of the questions was changed in order to introduce a slight difference between the tests; however, use of the same questions allowed direct comparison of responses between the two tests.

The first question, with its response options, is shown below:

1. In general, what does a capacitor do in an electrical circuit?

a. Generate a magnetic field	b. Store charge
c. Produce light	d. Slow down charge flow

Table 2 - First Question on Pre-Test (Third Question on Post-Test)

This is the most direct, and the simplest of the four questions. This does not test students' understanding of capacitor physics, per se; rather, it evaluates their familiarity with the device. The ability to define a concept is often the first step in understanding it. Moreover, with students initially unfamiliar with capacitors, this question serves two purposes. From an instructor's perspective, it gauges their learning of basic capacitor function. From a student's perspective, the question identifies the topic of the laboratory, and highlights its function as the main concept to be learned.

The second question is as follows:

2. What is the effect on the time constant, τ, of an RC circuit if the amount of charge that is stored in the capacitor for a given voltage is doubled, and the voltage supplied to the circuit is halved? a. τ decreases by a factor of 4   b. τ increases by a factor of 4 c. τ increases by a factor of 2   d. τ decreases by a factor of 2

Table 3 - Second Question on Pre-Test (Fourth on Post-Test)

This question addresses the time constant of an RC circuit, and gauges whether students know what factors affect it, as well as how each factor contributes to its value. This is the most quantitative question on the test; however, it was not presented as a numeric problem in order to avoid allowing the "plug-and-chug" approach in solving. In order for students to use the time constant formula to solve this problem, they would need to understand each variable as well as its effect. Additionally, the introduction of a change of voltage to the system, increases the challenge posed by the question, and further hinders the use of mathematical formulae.

The third question is given below:

3. What does the time constant of an RC circuit represent during charging? a. The time for the capacitor to fill with charge.   b. The time for the resistor to heat up completely. c. The time for the capacitor to fill with charge to about 3/5 of the complete amount.   d. The time for the battery to lose about 3/5 of its voltage to the capacitor

Table 4 - Third Question on Pre-Test (First on Post-Test)

This question tests students' understanding of the voltage and current characteristics of an RC Circuit during transient operation (ie, charging or discharging). Additionally, it implicitly requires knowledge of the linear relationship between the amount of charge stored in a capacitor and the voltage across it. The question also explicitly requires students to understand the nature of the exponential decay relationship that applies to the system; and, this requirement introduces an extra element of challenge into the question.

The fourth question is as follows:

4. The time constant of a charging RC circuit is 2s. Ideally, how much time will it take for the capacitor to discharge completely?	
a. 2s	b. 10s
c. 4s	d. An infinite amount of time.

Table 5 - Fourth Question on Pre-Test (Second on Post-Test)

This question is the most theoretical of the four, and also the most difficult. It presents a trick, in giving an irrelevant value for the time constant. Also, it requires understanding of the theoretical, exponential decay function that describes discharging. Implicitly, the question requires an understanding of the relationship between the time constant of a capacitor and its discharge behaviour. Finally, the options presented – three numerical possibilities and infinity – could also be confusing. Students who are unsure of the correct answer may shy away from choosing an infinite amount of time, both because it is so different from the other possibilities, and because it seems physically impossible. Of course, by the same token, this option might attract some students, entirely because of its abnormality.

Results of the Pre- and Post-Tests

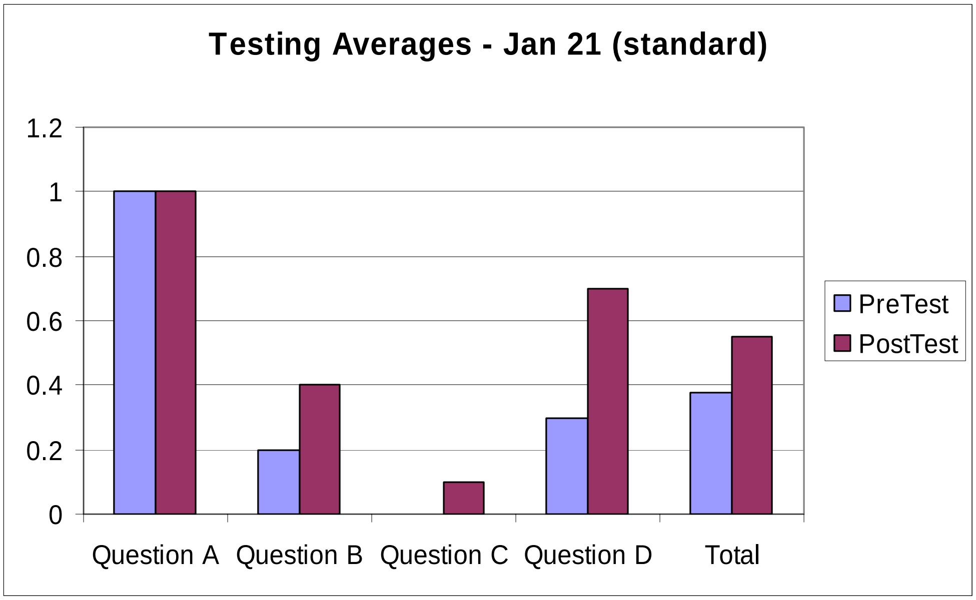
Analysis of the testing implemented in the RC Circuits lab consisted of question-per-question comparisons, total grade comparisons, and calculation of the Hake coefficient[58]. Hake defined the normalized gain as the improvement between two tests, relative to the possible improvement. Equation 1, below, expresses the calculation:

$$\boxed{g = \frac{(PostScore - PreScore)}{(100\% - PreScore)}}$$

Equation 1 - Calculation of the Hake Gain Coefficient

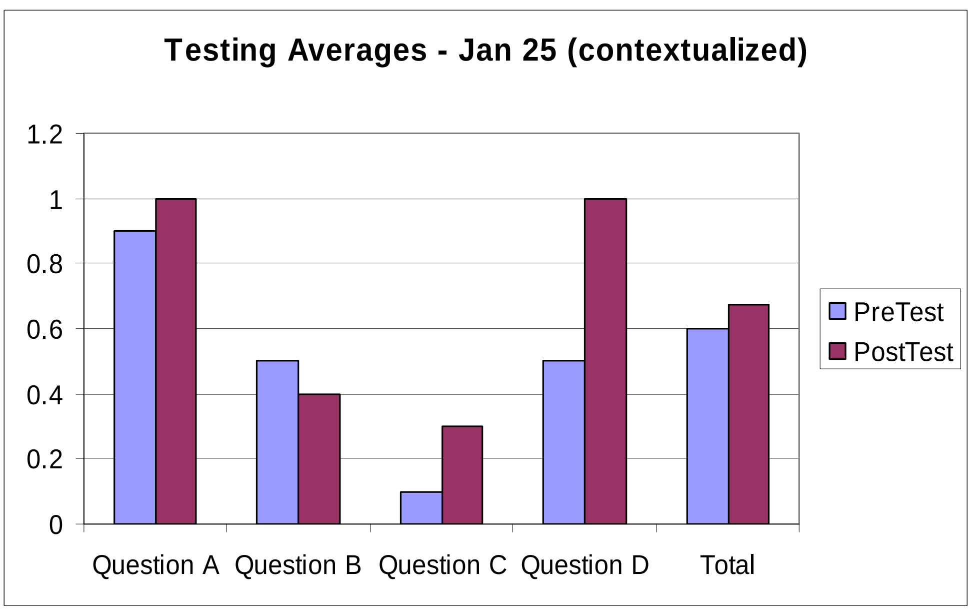
Equation 1 allows negative and even negative-infinite values for the normalized gain. In the following analysis, negative values were accepted, when encountered, but infinite values were taken as zero. That is, for a perfect pre-test grade, the gain is, at best, zero. Although the post-test grade is lower than that of the pre-test in the case of negative-infinite values of the pre-test, no acceptable comparable measure was found to account for this case.

The pre-test vs post-test averages for the four laboratory sessions are shown graphically below. The first two are for the "standard" procedure, the experiments of which were performed on January 21 (before the lecture on RC circuits) and on February 1 (after the lecture). The following two are for the "contextualized" procedure, the experiments of which were performed on January 25 (before the lecture on RC circuits) and on February 4 (after the lecture). Also listed, below each graph, are the class averages for the pre- and post-test, as well as the difference between them and the gain coefficient of the numbers. Note, that Question A is the "first question," as described in the earlier section of this report, Question B is the "second question," and so on. Refer to Appendix I for the original test results data.



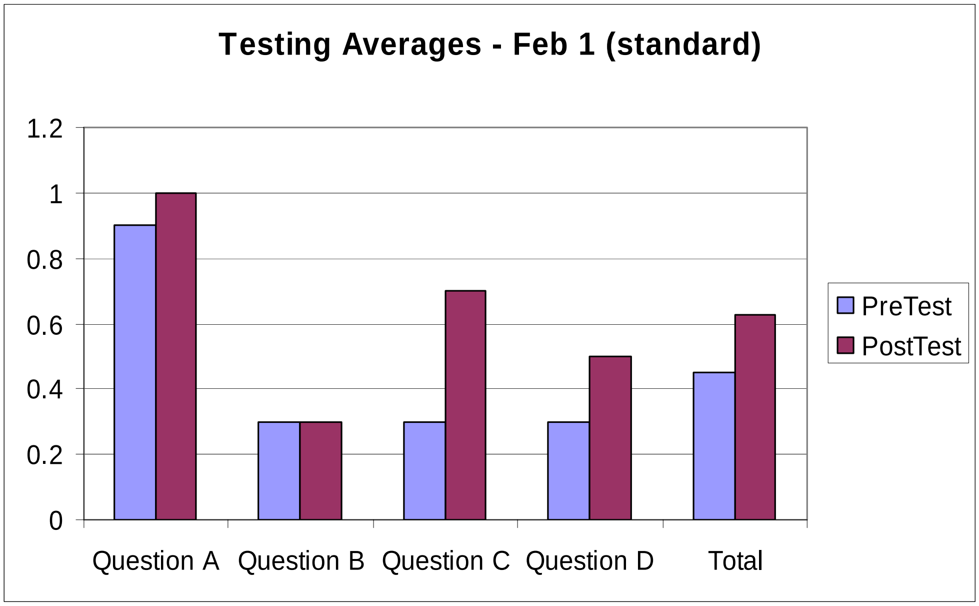
(Pre-Test Average: 37.5%; Post-Test Average: 55%; Δ=17.5%; g=0.28)

Figure 3 - Question Results and Test Scores for Jan. 21, "Standard" Laboratory



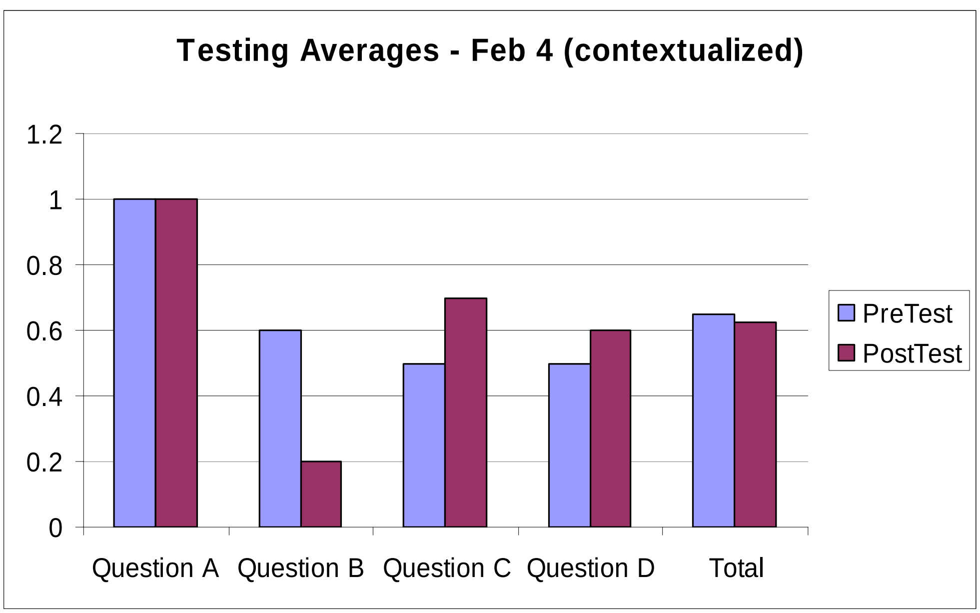
(Pre-Test Average: 60%; Post-Test Average: 67.5%; Δ=7.5%; g=0.19)

Figure 4 - Question Results and Test Scores for Jan. 24, "Contextualized" Laboratory



(Pre-Test Average: 45%; Post-Test Average: 62.5%; Δ=17.5%; g=0.32)

Figure 5 - Question Results and Test Scores for Feb. 1, "Standard" Laboratory



(Pre-Test Average: 65%; Post-Test Average: 62.5%; Δ=-2.5%; g=-0.07)

Figure 6 - Question Results and Test Scores for Feb. 4, "Contextualized" Laboratory

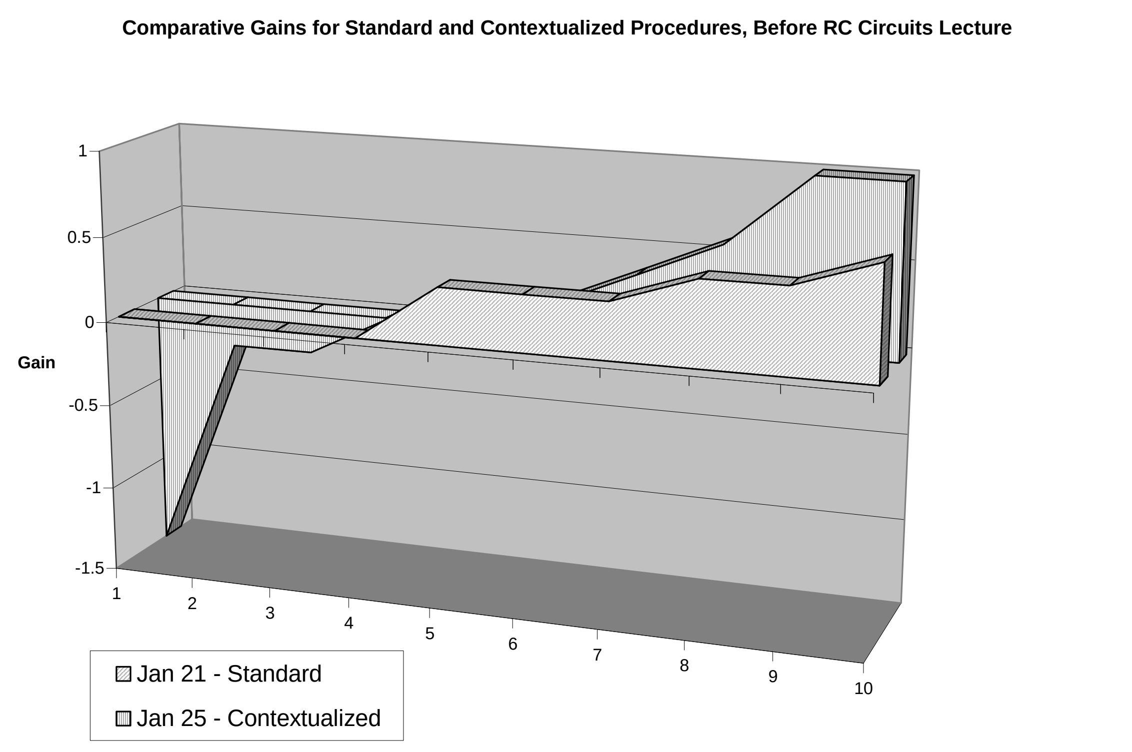
The results indicate a higher teaching effectiveness of the “standard” procedure, compared with the “contextualized” procedure. Both of the “standard” procedures showed higher a higher increase in test scores between the pre-test and the post-test values. In both cases, the pre-test averages for the “contextualized” procedures were significantly higher than those of the “standard” procedures, which may have contributed to the lessened relative improvement for the “contextualized” post-test scores. However, the gain coefficients account for pre-test grades; and, again, these values favoured the “standard” procedures as more effective, for both sets of laboratory sessions.

In general, the post-test class averages are not impressive. This could indicate a number of things. The test questions could have been too difficult for the scope of the experiment. Or, the questions could have been testing a different understanding altogether than that taught through the experiment procedures. Or, the experiment could have been unsuccessful at teaching the intended concepts. Further quantitative analysis, as well as qualitative observations from marking the students’ laboratory manuals, will explain the results further.

Analysis of Hake Coefficients of Laboratory Test Scores

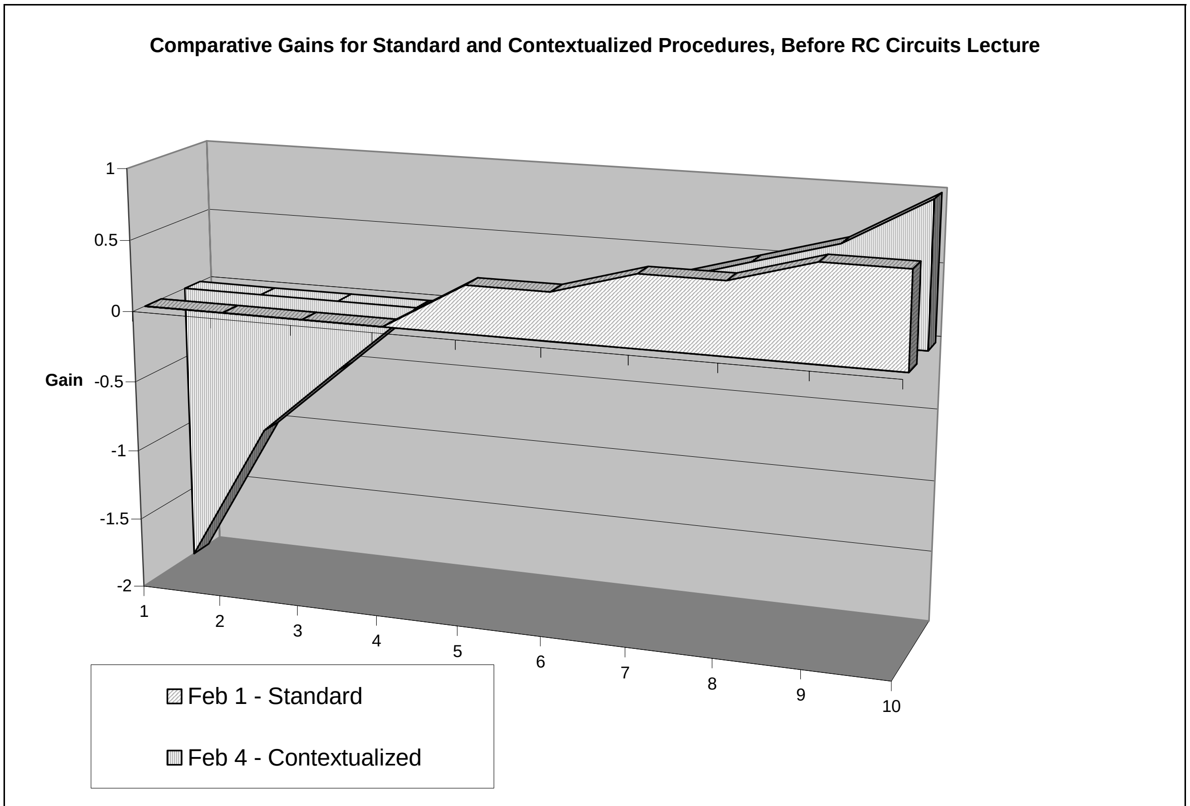
The Hake (ie, gain) coefficient describes the relative improvement, compared with possible improvement, between two test scores. Here, the gain of students grades on the pre- and post-tests are analyzed. As explained earlier, negative gain values are accepted, negative-infinite gain values are taken as zero.

The relative gains for students have been ordered from lowest gain to highest, and plotted to illustrate the implications of the results. The gains of the "standard" vs the "contextualized" procedures are shown below, separated by date (ie, those before the RC circuits lecture are grouped together, as are those after). Statistics of the individual gains are also included.



January 21, "Standard" Procedure Gain Distribution Statistics	*January 25, "Contextualized" Procedure Gain Distribution Statistics*
Sum: 2.7	Sum: 1.3
Average: 0.27	Average: 0.13
StdDev: 0.25	StdDev: 0.73

Figure 7 - Gain Distributions of Experiments Performed Before the RC Circuits Lecture



February 1, "Standard" Procedure Gain Distribution Statistics	*February 4, "Contextualized" Procedure Gain Distribution Statistics*
Sum: 3.0	Sum: -1.0
Average: 0.30	Average: -0.10
StdDev: 0.28	StdDev: 0.88

Figure 8 - Gain Distributions of Experiments Performed After the RC Circuits Lecture

These results, as do those of the marks distributions, indicate a higher effectiveness of the "standard" procedure over the "contextualized" procedure, contrary to what was expected. Moreover, these results indicate how poorly students performed after the "contextualized" procedure experiment with a very low average gain for the January 25 session, and with a negative average gain for the February 4 session.

To assess the effectiveness of the "standard" procedure, comparison is made with results cited by McDermott from a tutorial session[59]. On the pre-tests, roughly 5% of students answered correctly, and on the post-test, 40% of students answered correctly. Using these numbers as grades, the gain coefficient is 0.37. This is about 32% greater than the gain from the January 21 laboratory, and about 24% greater than the gain from the February 1 laboratory. Hence, if the testing used here does evaluate students' understanding with high accuracy, it seems that the RC Circuits experiment (in the best case, using results from the "standard" procedure) has an efficiency of roughly 70% of that of McDermott's teaching techniques. Of course, since the modes of instruction differ between the laboratory and the tutorial activity, direct comparison of these results may not be entirely valid.

Analysis of Electricity & Magnetism Term Test Results

On the term test for the Electricity & Magnetism section of PHY 138, to which the RC Circuits experiment pertains, a conceptual, multiple-choice question regarding capacitors in RC Circuits was asked. This question was inserted so as to facilitate comparison between the scores of students who performed the RC Circuits experiment with those of the rest of the class. The question pertained to the current in a simple RC Circuit during discharge, which the students were asked to calculate after a particular time. Though not purely conceptual in nature, it is thought that relative scores from this question should still indicate the instructional efficacy of the RC Circuits experiment.

The average test scores are graphed below, for each experiment session, compared with the overall class average. The effect of the grades of the 40 participating students on the overall class average was assumed to be negligible. Something to note is that one participating student's answer to the question was not known, due to confusion in the student's identification number. This student participated in the "standard" procedure experiment on February 1, and a correct response would have increased that session's average by roughly 2%, to a score of 80%.

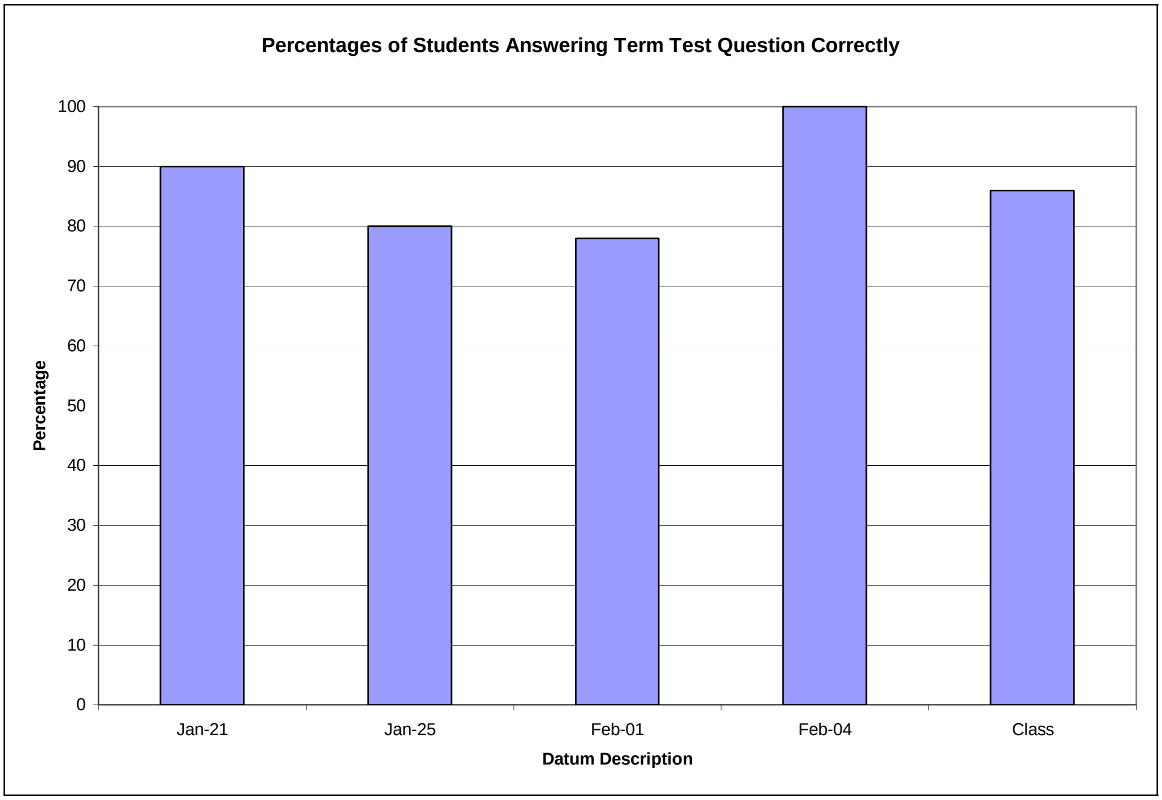


Figure 9 - Percentages of Correct Responses to RC Circuits Question on the Term Test

As the graph above indicates, one of each type of procedure yielded a marginally higher than average percentage of correct responses, and one of each type of response yielded a marginally lower than average percentage. One problem with this analysis is that the percentage of students in the entire class who answered the question correctly was very high, at 86%. This precludes a meaningful comparison, other than to note that the RC Circuit experiment did not seem to have a detrimental effect. Also, the timing of the laboratory session, whether prior to the RC circuits lecture or after it, did not seem to matter.

The total percentage of students who participated in the RC Circuits experiment, with either procedure, and who answered correctly, was 87.5%. This is 1.5% higher than the total class's percentage of correct responses; however, the margin of improvement is too small to be conclusive. Again, the percentage of correct responses in the class as a whole was very high, which prevents meaningful comparisons.

Summary of Results from the RC Circuits Experiment

As aforementioned, the results do not clearly indicate any effectiveness of the RC Circuits experiment to teach students about the function of capacitors in RC Circuits. Moreover, the “contextualized” procedure, which was postulated to be more effective, seemed to actually be less so at teaching the concepts. There are several possible reasons for these results, the following discusses some possibilities, and references qualitative observations made during the laboratory and while marking students’ informal laboratory reports.

One problem with the RC Circuits experiment could have been the apparatus used. Students were unfamiliar with the integrated circuit timer chip that was used to generate the output signal. The chip was treated as a black box throughout the experiment; and, students may not have been convinced of the effect of the connected capacitor on the frequency of the output. As aforementioned, mental models are influenced by observation of complete, understandable effects; and, the lack of knowledge pertaining to the timer chip could have inhibited learning in the laboratory. One of the most convincing corroborations to this argument is a comment made by a student in the informal report, as follows:

> *Perhaps a lab that dealt more with the circuit instead of being given the circuit would have allowed a better understanding of RC circuits. Also the usage of a complicated resistor system did not help in understanding the RC circuit.*
>
> – Excerpt from Student’s Lab Report from Feb. 1 (“Standard”)

Other potential problems related to the output signal. Many students did not fully understand the relation between frequency and period of an oscillating signal, as evidenced by questions in the laboratory. That is, several students had trouble determining how to obtain the time constant from the measured frequency. Without this knowledge, the ability to teach anything pertaining to the time constant, through observation of frequency, would be greatly compromised. Regarding the “contextualized” procedure, an extra cognitive step was required to relate the time constant of the apparatus circuit to the observations. Students may not have associated sound with frequency; hence, hearing different tones produced may have had no effect at teaching them about frequencies and time constants. However, student remarks in their informal reports from the "contextualized" procedure laboratories indicate that at least a few of them understood that a low pitch meant a low frequency, and vice versa.

Furthermore, observation of beats in the "contextualized" procedure was difficult. Students were often unsure of whether or not they were hearing beats, and sounds from nearby apparatus further confused observation. This difficulty could have frustrated students, and it also could have widened the gap between what they observed in the lab and the concepts pertaining of RC circuits that were intended to be taught.

A final factor that may have influenced the relative effectiveness of the two procedures are students' Auditory, Visual and Kinesthetic (AKV) learning styles[60], which were not considered during development of the experiment. People generally respond differently to different sensory stimuli; and, individuals learn most effectively when information is presented in a manner that corresponds to their particular learning styles. Predominantly auditory learners respond best to verbal communication, visual learners learn most effectively from pictures and animations, and kinesthetic learners are most receptive to tactile stimulus. The two procedures for the RC Circuits experiment differ in the type of stimulus most prevalent in the observation techniques. The "standard" procedure allows visual observation using the oscilloscope, whereas the "contextualized" procedure allows auditory observation of beats. With reference to AKV learning styles, a student could learn more effectively from one procedure than from the other, simply on the basis of the manner of observation that corresponds best to her/his individual style. In future research, experiment procedures should permit a variety of types of sensory observation, in equal proportions.

Conclusions Pertaining to the RC Circuits Experiment

The RC Circuits experiment was not distinctly effective at teaching students about capacitors and their function, compared with techniques used in lecture. Moreover, the "contextualized" procedure was less effective than the "standard" procedure, which may have been caused by added observational and conceptual difficulties in the approach of the "contextualized" procedure.

Overall, both procedures aimed to test whether a story line approach, applied to the laboratory, would be effective at teaching the concepts in the course. Evidenced by the high percentage of students who answered correctly on the applicable term test question, the regular curriculum of PHY 138, with the PER-guided innovations addressed earlier, was already effective at teaching students about capacitors and RC circuits. Furthermore, this complicated the analysis of results from the participating students. While some positive variation over the class background was seen in the results from participating students, it is not thought that this constitutes corroborating evidence of teaching effectiveness.

The "contextualized" procedure, specifically, aimed to test the effectiveness of incorporating real-world context into experiments in the introductory physics laboratory. Based on the aforementioned elements of the observation procedure that likely confused the students, it cannot be concluded whether the results indicate failure of this approach or error in its implementation. The results do, however, highlight the difficulty in adding real-world context into introductory physics laboratories. Hence, added caution should be used in further attempts to implement this; nonetheless, it would be interesting to observe the actual effect of such a context on student learning.

In general, PER is a complicated field. Teaching, in general, is difficult, because a very large number of factors, many of them unknown, contribute to learning. Teaching physics is especially difficult, because the subject matter is highly conceptual. Finally, teaching introductory physics is even more challenging, both because of students' preconceived notions of the phenomena, as well as due to the constraints of teaching concepts in enough detail for students to accept them, but with little enough detail for students to be able to understand them. Introductory physics education is a balancing act, and well-deserved applause should be given to those who do it well.

Appendices

Appendix A[61] – Marking Scheme of PHY 138:

Component	Weight
Assignments and Pre-class Quizzes	15%
Tests	30%
Laboratory	20%
Final Exam	35%

Appendix B[62] – PHY 138 Course Organization:

Lectures

Lectures in PHY138 are intended as an introduction to some of the course material. There are 2 lectures per week.

- **When?** Monday and Wednesday, from 11 to 12 noon. (At the University of Toronto, all classes start at 10 minutes past the hour and end precisely on the hour. Thus, the lectures actually begin at 11:10.)
- **Where?** Convocation Hall

The course has been divided into four sections, each lasting one-quarter of the academic year, and corresponding to the four major topics in the curriculum.

Each section is taught by a different lecturer. This will give you the opportunity to see Physics from the perspective of four different individuals.

The section topics with their lecturers are, in order:

Topic	Lecturer
Mechanics	David Harrison
Waves	Jason Harlow
Electricity and Magnetism	William Trischuk
Nuclear Physics and Radiation	Tony Key

Each lecture will be recorded (audio only) and, within a day or two, posted in two formats on the course website. Due to disc-space limitations, and to encourage you to use this facility in good time, the recordings will be available **for three weeks** after they are posted. You can access the recordings by following the appropriate links on the course home page.

Please be aware that not all the material on which you will be examined will be discussed in lectures. You will be asked to read sections in the textbook ahead of lectures. Although you may be responsible for the whole of the section, only some of it will be taken up by the lecturer. Of course, you are welcome to ask questions about any examinable material, whether or not it has been discussed in class.

To provide you with an incentive for keeping up to date on your reading, about once a week you will be asked to answer a short on-line quiz on assigned reading material before part of it is discussed in the lectures.

Tutorial Info (groups, TAs, locations)

Tutorials give you the opportunity to discuss Physics, ask questions, and work on problems in the context of a small group. Each tutorial is led by a *Tutor*, typically a graduate student in the Department of Physics working towards his/her Masters degree or PhD. Normally, you should be in the same tutorial with the same Tutor throughout the academic year.

For almost all students, this opportunity to meet in small groups to discuss the content of the course is an extremely valuable educational experience, and we urge you to attend the tutorials regularly. Just as for the lectures, however, we shall not be taking attendance at tutorials. Note that this is different from the laboratory, where attendance at each of your regularly scheduled laboratory sessions is mandatory.

The tutorial sessions will often make use of McDermott & Shaffer's **Tutorials in Introductory Physics** as workbooks, so be sure to bring them with you to tutorial. This is important as many homeworks will contain questions from McDermott & Shaffer and will assume that some preliminary work has been done in tutorial.

Appendix C[63] – PHY 138 Course Curriculum:

FIRST QUARTER: MECHANICS

1. Introduction and Vectors (§1.1-§1.5, §1.7-§1.9, §1.11)
2. Motion in one Dimension (omit §2.8)
3. Motion in two Dimensions (§3.1-§3.5)
4. Force and Newton's Laws of Motion (omit §4.8)
5. Applications of Newton's Laws (§5.2, §5.3, §5.6, §5.7)
6. Energy and Energy Transfer (omit §6.7, §6.9)
7. Potential Energy (§7.1-§7.4, §7.7)
8. Momentum and Collisions (§8.1-§8.4)
9. Rotational Motion (omit §10.6, §10.11, §10.12)

SECOND QUARTER: WAVES

1. Simple Harmonic Motion (§12.1-§12.3)
2. The Pendulum, Resonance (§12.4,§12.7)
3. Wave Propagation, Travelling Waves, Reflection (§13.1-§13.5)
4. Sound, Doppler Effect (§13.7, §13.8)
5. Superposition and Interference of Waves (§14.1, §14.2, §14.3)
6. Standing Waves, Harmonics (§14.4,§14.5)
7. Light, Lasers (§24.3, §24.7, §24.9)
8. Ray-tracing, Reflection, Refraction, Dispersion, Total Internal Reflection, Optical Fibres (25.1-§25.4, §25.7, §25.8)
9. Mirrors, Lenses (§26.1, §26.4-§26.6)

THIRD QUARTER: ELECTRICITY AND MAGNETISM

1. Electric Forces (§19.2 -> 4)
2. Electric Fields (§19.5, §19.6)
3. Electric Potential Energy (§10.1, §20.2, §20.10)
4. Electric Potential (§20.3, §20.4)
5. Equipotentials, Energy in Capacitors (§20.7 -> 9)
6. Currents, Resistance and Resistivity (§21.1, §21.2, §21.5)
7. Resistance and Circuits
8. Kirchoff's Laws
9. RC Circuits
10. Magnetic Fields
11. Magnetic Forces
12. Electromagnetic Induction, Inductors

FOURTH QUARTER: NUCLEAR PHYSICS AND RADIATION

TBA

The missing information will be included as soon as it becomes available.

Appendix D[64] – Transcript of Survey Given to PHY 138 Students:

In PHY138 this year we are trying some new ways to help you learn physics. Please take a couple of minutes to answer some questions about these innovations. For all questions that you answer, choose from 1 to 7 where:
1 means: totally useless
4 means: neutral
7 means: an invaluable aid to my learning

1. In-Class Questions: In class many times I asked the class a question and asked for a vote of what you thought was the correct answer. How useful were these questions?

1 2 3 4 5 6 7

2. Small Group Discussion: When there was disagreement on the right answer to an In-Class Question, often you broke up into small groups to discuss it. How useful were these small group discussions?

1 2 3 4 5 6 7

3. Demonstrations: Often we did demonstrations in class, sometimes in conjunction with In-Class Questions and small group discussions. In general, are demonstrations useful?

1 2 3 4 5 6 7

4. Flash Animations: Often we used Flash animations in class. In general, were these animations useful?

1 2 3 4 5 6 7

5. Pre-Class Quizzes: Almost every week you did a short quiz on the textbook readings for the next 2 classes. How useful were the Pre-Class Quizzes?

1 2 3 4 5 6 7

6. MP Problem Sets: Almost every week you did a problem set using *MasteringPhysics* software. How useful were the MP Problem Sets?

1 2 3 4 5 6 7

7. Written Homework: Although not an innovation but a traditional technique, almost every week you had a Written Homework Assignment. How useful were the Written Homework Assignments?

1 2 3 4 5 6 7

8. McDermott Tutorials: Three times this quarter you used materials from the green *Tutorials in Introductory Physics* workbooks. How useful were these tutorial activities?

1 2 3 4 5 6 7

9. Tablet PC: Instead of *PowerPoint*, the main content of the classes was delivered using the *Journal* program on a Tablet PC. **Compared to a *PowerPoint*-based class like BIO150**, how effective is this technology for your education?

1 2 3 4 5 6 7

Appendix E[65] – Comparative Results of Fall and Spring Surveys:

PHY138 - Teaching Techniques Survey - 2004/2005

We have surveyed PHY138 students about some of the teaching techniques that we have been using this year. We surveyed the students twice, with almost identical questions both times. The first survey was during the sixth week of classes (Oct. 20 - 22), and the second was during the twenty-first week of classes (March 9 - 11). The survey was conducted in tutorials.

I will not discuss the results in any detail: they mostly speak for themselves.

A *pdf* of the first survey form is available via the button to the right. Below we indicate changes in the survey form that was used in March.

Click Me

669 students responded to the first survey; this was about 67% of the class.
311 students responded to the second survey; this is about 35% of currently enrolled students.

The answer to each question is a number between **1** and **7**, with higher numbers positive; neutral is **4**. The **Summary** column was calculated as follows:

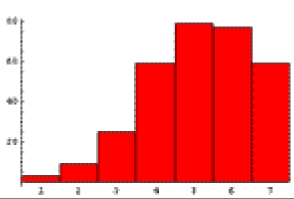
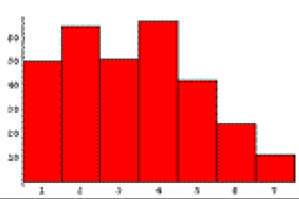
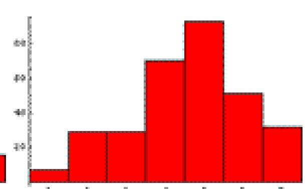
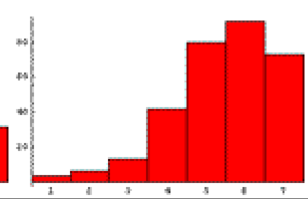
- The percentage of responses that were **1**, **2**, or **3** is the ***negative percentage***.
- The percentage of responses that were **3**, **4**, or **5** is the ***neutral percentage***.
- The percentage of responses that were **5**, **6**, or **7** is the ***positive percentage***.
- Unless two of the above are close to each other, only the highest is reported.

	When	Mean	Summary	Comment
In-Class Questions	Fall 2004	5.32	76% ***positive***	Conceptual questions in multiple-choice format; the students raise their hand to indicate their answers. In mid-October we converted to colored cardboard squares so that all students "vote" at once.
	Winter 2005	5.15	69% ***positive***	Except for the 3rd quarter, these continued in almost every class. Unless we can get RF clickers into Con Hall, we will make the colored cardboard squares part of the textbook package next year.
Small-Group Discussion in Class	Fall 2004	3.87	58% ***neutral***	These were based on the *In-Class Questions*. The relatively poor evaluation is perhaps related to the fact that our students performed quite differently from their American counterparts on these questions, usually much better. Thus, the discussions were not always effective, but sometimes seemed to be very effective.
	Winter 2005	3.33	53% ***negative*** 52% ***neutral***	

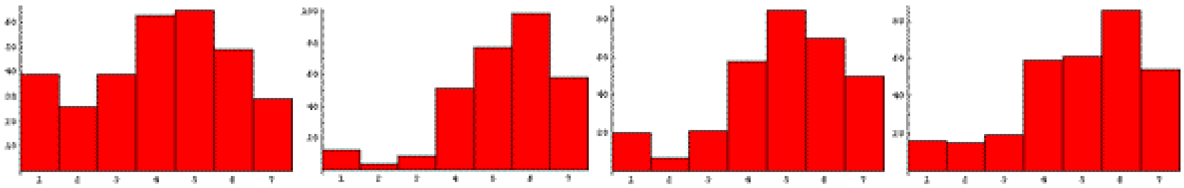
Demonstrations	Fall 2004	5.33	74% ***positive***	Students *like* demonstrations. Making them effective learning tools is another story. A recent study is available here.
	Winter 2005	4.59	62% ***neutral*** 57% ***positive***	
Flash Animations	Fall 2004	5.11	72% ***positive***	With the exception of the third quarter, Flash animations were used in many classes. They are always available to the students via the web.
	Winter 2005	5.45	79% ***positive***	
Pre-Class Quizzes	Fall 2004	3.71	53% **neutral**	These are nearly-trivial quizzes designed to insure that the students have read the text before class. Despite the students' relatively low opinion, I believe it is very important that the students read the text before class.
	Winter 2005	4.14	54% **neutral**	
MP Problem Sets	Fall 2004	4.58	58% ***positive***	These are on-line problem sets using *Mastering Physics* software. We are very impressed with the quality of the questions and the philosophy used by the software.
	Winter 2005	5.26	75% ***positive***	
Written Homework	Fall 2004	4.58	56% ***neutral*** 56% ***positive***	
	Winter 2005	4.90	66% ***positive***	
McDermott Tutorials	Fall 2004	3.48	48% ***negative*** 54% ***neutral***	See below
Tablet PC	Fall 2004	4.08	See below	
	Winter 2005	4.96	65% ***positive***	

Histograms

The above numeric information tells almost all of the story about these surveys. Nonetheless, for completeness, here are histograms of the results of the Winter 2005 survey.

In-Class Questions | Small-Group Discussion | Demonstrations | Flash Animations



Pre-Class Quizzes | MP Problem Sets | Written Homework | Tablet PC

About McDermott Tutorials

These are conceptual activities done by small groups of students. In the first and second quarters, we used these a fair amount. We discovered that the activities were often too simple for our students. When the level was correct, we believe they were quite effective.

In the third quarter of the course they were not used to a significant degree. In the fourth quarter, there were no available tutorials on the topics of the class so the workbooks were not used at all. Thus we did not ask this question in the Winter 2005 survey.

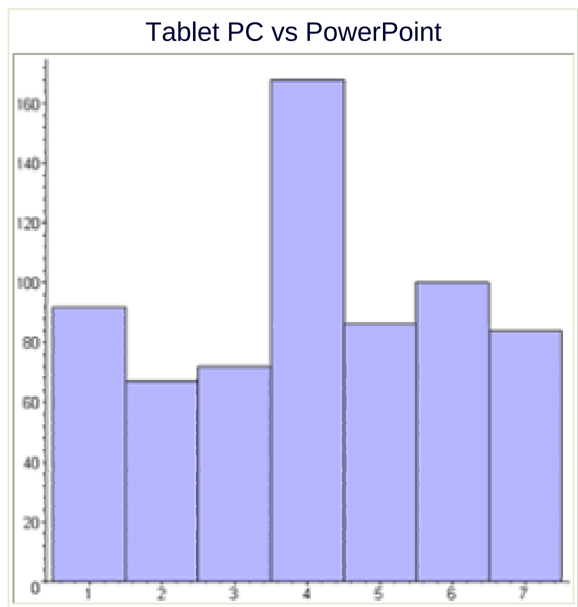
About the Tablet PC

With the exception of the third quarter, the Tablet PC is used as an electronic blackboard projected onto the main screen in Con Hall. In the third quarter, the classes were PowerPoint-like with the Tablet PC being used to annotate the slides of the presentation.

In the first survey the question that we asked was:

Instead of *PowerPoint*, the main content of the classes was delivered using the *Journal* program on a Tablet PC. Compared to a *PowerPoint*-based class like BIO150, how effective is this technology for your education?

It is not clear to me what we were asking in this mal-formed question, and I wrote it! A histogram of answers appears to the right. With the exception of the neutral answer **4** the shape is essentially flat.



Appendix F[66] – Marking Scheme for Laboratory Component of PHY 138:

	Fall Term (F)	Spring Term (S)
Error Analysis Assignment	10%	-
Height of the Physics Building Assignment	5%	-
Experiment Mark (notebook, work in lab)	45%	55%
In-Lab Mark (work in lab)	15%	25%
Formal Report (scientific)	20%	20%
Errtst (computer test on errors)	5%	-

Lab Mark = 0.5*F + 0.5*S

Appendix G – RC Circuits Laboratory Guide, “Standard” Procedure:

Resistor-Capacitor (RC) Circuits

References:

- RC Circuits:

  Most Introductory Physics texts (e.g. A. Halliday and Resnick, *Physics* ; M. Sternheim and J. Kane, *General Physics*.)

- Electrical Instruments:

  Online Laboratory Manual: *Commonly Used Instruments: The Oscilloscope* (faraday.physics.utoronto.ca/IYearLab.html)

  Stanley Wort and Richard F.M. Smith, *Student Reference Manual for Electronic Instrumentation Laboratories* (Prentice Hall 1990).
  Also see the video - *Physics Skills; How to use the Oscilloscope* - starring Dr D.M. Harrison.

Objectives:

This laboratory will allow you to observe:

- How a capacitor functions in electrical circuits.
- How the time constant of an RC circuit relates to the resistance and capacitance.
- How an RC circuit can be used to produce an “Alternating Current” (AC) signal.
- The relation of the frequency of this AC signal to the time constant of the circuit.

Introduction:

An RC circuit is an interesting and important electrical device, which can be used for many different purposes. In this laboratory, you will use an RC circuit to generate an AC electrical signal with the help of a simple computer chip. The frequency of the signal produced will depend on the values of the resistor and capacitor used in the circuit. Your circuit will be connected to an Oscilloscope, which will allow you to observe and measure the frequency of the signal produced.

Background

- Resistance:

  A resistor is an electrical device that slows down current flow (the rate of net electron motion) through a circuit. Resistance is the property that measures the strength of a resistor, and this term is also used to describe the slowing effect of many other electrical devices on current flow. By Ohm’s law:

  $V_R = IR$ where V_R is the voltage, measured in Volts; I is the current, measured in Amperes (Coulombs per second); and R is the resistance, in Ohms

  Equation 2 - Ohm's Law

  Equation 1 means that the resistance of a component determines the current flow through it for a given applied voltage.

- Capacitance:

  A capacitor is an electrical device that stores charge, that is, free electrons and positive ions. Capacitance is the property that measures how much charge will eventually be stored in a capacitor, for a given applied voltage. The larger the capacitance of a capacitor, the more charge will be stored:

  $C = q/V_C$ where V_C is the voltage across the capacitor, measured in Volts; q is the charge stored, measured in Coulombs; and C is the capacitance, measured in Farads

Equation 2 - Capacitor Voltage

When a capacitor is connected to a voltage source, like a battery, as shown in Figure 1 below, it fills with electric charge. As charge builds up, electrostatic repulsion causes a voltage to develop across the capacitor. This voltage always opposes the external voltage, until the two balance each other, and no more charge is stored. For the circuit configuration in Figure 1, when the capacitor is charged, the current in the circuit will be zero. When discharging, as in Figure 2 below, the voltage across the capacitor, due to electrostatic repulsion, decreases as the electrostatic charge buildup decreases.

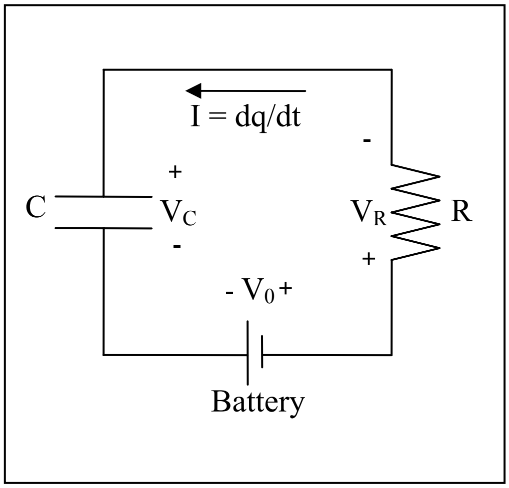


Figure 1 - RC Circuit Diagram (Charging)

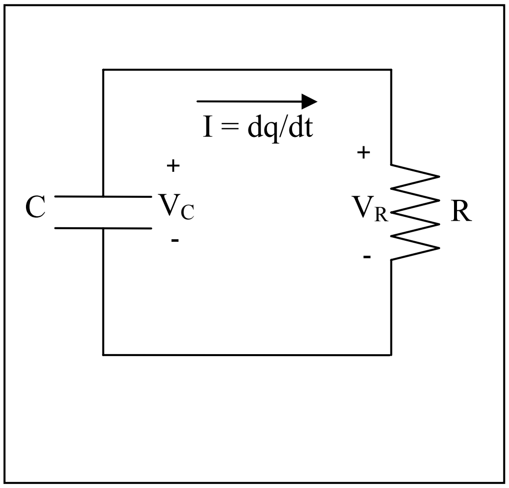


Figure 2 - RC Circuit Diagram (Discharging)

For both charging and discharging, the resistor limits the current in the entire circuit and prevents the wire from burning out. As you might guess, the capacitance and the resistance both affect the charge/discharge time.

- <u>Time Constant of an RC Circuit:</u>

The time constant of an RC circuit describes the charge/discharge time of the capacitor, and both the resistance and capacitance affect its value. The voltages and currents in an RC circuit follow exponential decay functions when charging and discharging. In fact, this behaviour is seen in any process where the rate of change of a quantity is directly proportional to the quantity itself.

The expression for the time constant of an RC circuit can be derived from examining either charge or discharge. Here, capacitor discharge will be used, and the relevant circuit is shown in Figure 2, above. It can be shown from Kirchoff's Voltage Law for the circuit:

$$V_C(t) + V_R(t) = 0$$

$$\Rightarrow V_C(t) = V_0 e^{-\frac{t}{RC}}$$

(Implicitly, a first-order, ordinary differential equation was solved to get to the second line.)

Figures 3 and 4 below show capacitor voltage for charge and discharge:

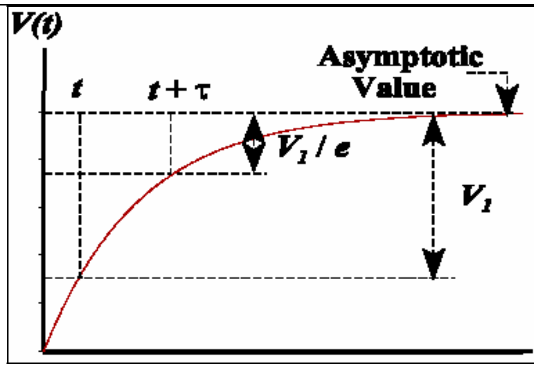


Figure 3 - Capacitor Charging

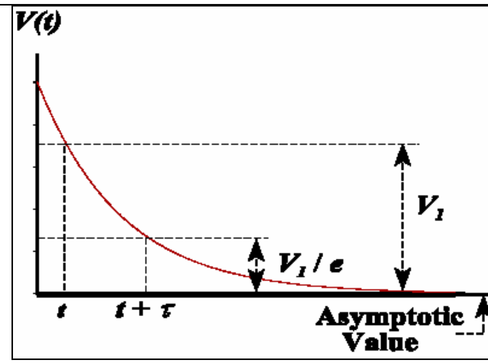


Figure 4 - Capacitor Discharging

As you can see, exponential decay is an asymptotic function, so the time to completely charge or discharge is theoretically infinite. However, a unique description of exponential decay time is given by the time constant, τ. The time constant is the time for a quantity to drop to $1/e = 0.368$ times its current value, or to increase by 1 - 1/e = 0.632 to its maximum. As shown below, the time constant of an RC circuit is calculated as the resistance multiplied by the capacitance:

$$V_C(\tau) = V_0\left(1 - e^{-\frac{\tau}{RC}}\right) = V_0\left(1 - e^{-1}\right) \Rightarrow \tau = RC$$

Equation 3 - τ of an RC Circuit (Charge)

$$V_C(\tau) = V_0 e^{-\frac{\tau}{RC}} = V_0 e^{-1} \Rightarrow \tau = RC$$

Equation 4 - τ of an RC Circuit (Discharge)

Apparatus Function

- <u>Creating an AC Signal Using an RC Circuit:</u>

The apparatus you will use in this lab is a simple RC circuit connected to a special computer chip called a timer. You can think of the chip as a much simpler (and cheaper), non-programmable version of the chip that runs a personal computer. The chip outputs an AC signal, the frequency of which is determined by the time constant of the attached RC circuit.

The AC signal produced by the timer chip is called a voltage "square wave," because the transition between maxima and minima is much more sudden than in smoother, sinusoidal signals. The frequency of the output square wave, as with any shape of wave, is the number of periods per second, and is measured in Hertz. (One period is one full high and low voltage cycle. One Hertz is one period per second.) The frequency of the output square wave is calculated:

$$\tau_{timer} = R_{eff} C$$

Equation 5 - Timer Chip Time Constant

$$f = \frac{1}{\ln 2 \cdot \tau}$$

Equation 6 - Timer Chip Output Frequency

In Equation 5, the R_{eff} is the effective resistance of the connected resistors combined with the internal resistances of the chip. C is the capacitance of the attached capacitor. In Equation 6, the factor of ln2 accounts for the charge and discharge times, both of which make up a single cycle.

Apparatus Setup

Figure 6, below, shows the apparatus used to create an AC signal, with frequency dependent on the attached capacitance. (In your circuits, the resistance cannot be changed – one task will be two determine the value of the total effective resistance of the circuit.) The basic apparatus consists of a circuit board, to which the timer chip, resistors, power supply (a 9V battery) and activation button have been connected:

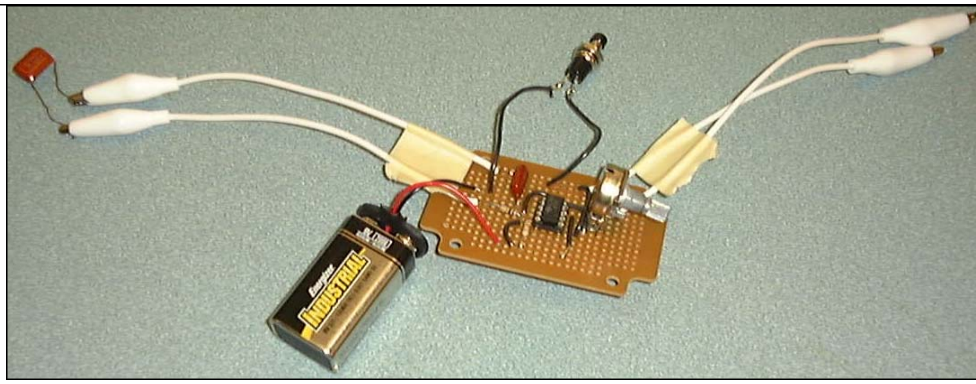


Figure 6 - Circuit Apparatus

The two alligator-clip wires labeled “C” should be attached to the capacitor being used. (Note, the capacitors you will use have no polarity, so it does not matter which way you connect the capacitor.) The two alligator-clip wires labeled “OUT” are for the AC output signal. You will connect these to other equipment in order to observe the frequency of the output signal. The final component to note on the circuit board is a potentiometer – it is a variable resistor that can be adjusted with a knob. It controls the voltage amplitude of the output signal, and you will learn more about it in the Preliminary Exercises.

Preliminary Exercises:

<u>**Observing Output Frequencies**</u>

1. Connect the 0.036μF capacitor and to the circuit apparatus, and connect the output leads to the Oscilloscope using the BNC-Alligator Clip cable (see Figure 7).

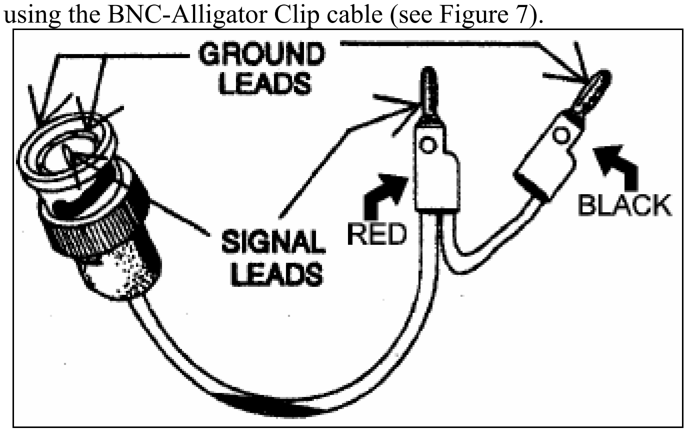


Figure 7 - BNC-Alligator Clip Cable

2. Press the button and adjust the Oscilloscope display so that you clearly see a square wave. Refer to Appendix I for instructions regarding the Oscilloscope.
3. Describe the wave that you see. Are the peaks purely symmetric? Are the crests the same width as the valleys? Will these features have any affect on the frequency of the wave?
4. Repeat steps 1-3 using capacitor 0.0022μF. Qualitatively compare different the waveforms produced in terms of their shapes and apparent frequencies. Explain your observations with relation to the capacitances in question.

<u>**Measuring Output Frequencies**</u>

1. Connect the 0.036μF capacitor to the circuit apparatus and view the output on the Oscilloscope. Adjust the display to clearly show individual periods.
2. Measure the frequency of the wave. This can be done by counting the full periods within a given time interval. Remember that 1Hz equals one peak per second, and make sure to account for reading error in your measurement. You should read a value of about 185Hz.
3. Repeat steps 1-2 with the 0.0022μF capacitor. You should read a value of about 3250Hz.

Procedure:

The two capacitors you worked with in the Preliminary Exercises will be the first two data in your experiment. You will use at least four of the remaining labeled capacitors (ie, those for which the capacitance is given) to plot the frequency vs capacitance relationship of your apparatus. What mathematical relationship do you expect your data to follow? To what extent does your experimental data agree with your theoretical predictions? Be sure to include error bars on data points.

Plot the time constant vs capacitance relationship of your circuit, using the data you have recorded. Using a graphing program or by hand, fit a curve to your data. What shape do you expect this curve to have? Can you write an equation for the curve? Does this equation agree with theory?

Determine the capacitances of one of the unlabeled capacitors by measuring the resulting time constants of the apparatus and fitting the data to your graph. The TA will have the actual values of the capacitances, and you can obtain these for comparison.

What is the effective resistance of the RC circuit that is driven by the timing chip? Does this agree with the resistors used, based on what you know about the function of the chip? Be sure to include error margins in your values, using the appropriate method of propagation of errors. Discuss the sources of these errors.

Appendix H – RC Circuits Laboratory Guide, "Contextualized" Procedure:
Note: Repeated sections from Appendix I have been omitted.

Resistor-Capacitor (RC) Circuits

References:

- RC Circuits:
  Most Introductory Physics texts (e.g. A. Halliday and Resnick, *Physics*; M. Sternheim and J. Kane, *General Physics*.)

Introduction:

An RC circuit is an interesting and important electrical device, which can be used for many different purposes. In this laboratory, you will use an RC circuit to generate an AC electrical signal, with the help of a simple computer chip. The frequency of the signal produced will depend on the values of the resistor and capacitor used in the circuit. Your circuit will be connected to an audio speaker, which will allow you to observe and measure the frequency of the signal produced.

Preliminary Exercises:

Observing Output Frequencies

1. Connect the 0.036μF capacitor and a speaker to the circuit apparatus.
2. Press and hold the button to hear the tone produced. (Note, to stop the speaker from vibrating on the lab desk, hold it in your hand facing up.)
3. Qualitatively describe the sound you hear. Consider factors such as pitch (or tone) and volume. Is the sound steady, or can you hear it interrupting and/or altering? Does the sound seem distorted (eg, think of how a radio station sounds when it is not being received clearly)? The sound should be uninterrupted and of a single and undistorted pitch.
4. Repeat steps 1-3 with the 0.0022μF capacitor.
5. Compare the tones produced by the different capacitors. Explain your observations with relation to the capacitances in question.

Using the Frequency Generator and Observing Beats

1. Connect the BNC-Alligator Clip cable (shown in Figure 7 below) to the MAIN OUT jack on the Wavetek Function Generator. Select a Square Wave and set the frequency to 185Hz. The Attenuator button should not be depressed, and the Potentiometer should be at half-maximum. (Refer to Appendix I for more information.) Attach the alligator clips to a speaker.

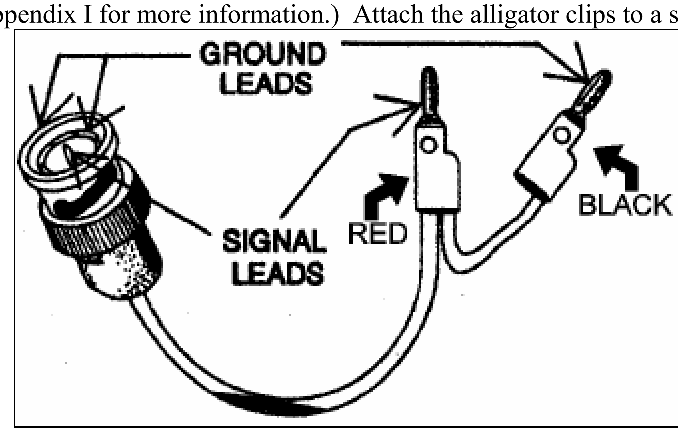


Figure 7 - BNC-Alligator Clip Cable

2. Turn on the Function Generator using the switch at the back and listen to the sound produced. Compare this sound with your observation of capacitor ***C1*** connected to the circuit apparatus in Part A.
3. Repeat steps 1-2 at a frequency of 3250Hz.
4. Connect the 0.036μF capacitor and set the Function Generator to 185Hz.
5. Activate the circuit and the Function Generator simultaneously. The two speakers should be

side by side, both facing upwards. The tone should not sound steady; rather, it should seem to pulsate quickly. This is the beating phenomenon, which occurs when two sounds of equal pitch and volume are played simultaneously and nearby. You will use this physical effect to measure the frequency of the output signal.

6. If you do not hear beats, adjust the Potentiometer on the circuit apparatus and the Potentiometer on the Function Generator so that the two outputs are at the same volume.
7. If you still do not hear beats, adjust the Frequency knob slightly about 185Hz The frequency may be incorrect, or you may not have recognized beating.

Appendix I – Pre- and Post-Test Grades from RC Circuits Experiment:

January 21 – "Standard" Procedure

Pre_A	Pre_B	Pre_C	Pre_D	Post_A	Post_B	Post_C	Post_D
1	0	0	0	1	0	0	1
1	0	0	0	1	0	1	0
1	0	0	0	1	1	0	1
1	1	0	1	1	1	0	1
1	0	0	0	1	0	0	1
1	0	0	0	1	0	0	0
1	0	0	1	1	1	0	1
1	0	0	1	1	1	0	1
1	0	0	0	1	0	0	0
1	1	0	0	1	0	0	1

January 25 – "Contextualized" Procedure

Pre_A	Pre_B	Pre_C	Pre_D	Post_A	Post_B	Post_C	Post_D
1	1	0	1	1	1	1	1
1	0	0	1	1	1	0	1
1	0	0	0	1	0	1	1
1	0	0	1	1	0	0	1
1	1	0	0	1	0	0	1
1	0	0	0	1	0	0	1
1	1	0	1	1	0	0	1
1	0	0	0	1	1	1	1
1	1	1	1	1	1	0	1
0	1	0	0	1	0	0	1

February 1 – "Standard" Procedure

Pre_A	Pre_B	Pre_C	Pre_D	Post_A	Post_B	Post_C	Post_D
1	1	1	1	1	0	1	1
1	0	0	0	1	0	1	0
1	1	1	1	1	0	1	1
1	0	1	0	1	0	1	0
1	0	0	1	1	0	1	1
1	0	0	0	1	0	1	1
1	1	0	0	1	1	0	0
1	0	0	0	1	0	1	0
1	0	0	0	1	1	0	1
0	0	0	0	1	1	0	0

February 4 – "Contextualized" Procedure

Pre_A	Pre_B	Pre_C	Pre_D	Post_A	Post_B	Post_C	Post_D
1	1	1	1	1	0	1	1
1	1	0	0	1	0	0	0
1	0	1	1	1	1	1	1
1	0	0	0	1	1	1	0
1	1	0	0	1	0	1	1
1	1	1	0	1	0	1	0
1	0	1	1	1	0	1	1
1	1	0	1	1	0	0	0
1	1	1	1	1	0	1	1
1	0	0	0	1	0	0	1

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