I, Carol Fabby, hereby submit this original work as part of the requirements for the degree of Master of Science in Physics.

It is entitled:
Reforming the introductory laboratory to impact scientific reasoning abilities

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Reforming the introductory physics laboratory to impact scientific reasoning abilities

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Abstract

Research indicates that students enter college with wide variations in scientific reasoning abilities, and it also suggests that students with formal reasoning patterns are more proficient learners. Unfortunately, these abilities are not impacted in the typical college course. In an effort to better target the development of scientific reasoning abilities of students in our introductory physics lab courses, we have revised the structure of the lab activities while maintaining the same topics and equipment we have been using for years in a more traditional lab setting. The changes enable students to become more involved in the actual design of the experiments and place more emphasis on student use of evidence-based reasoning. The challenges in implementing these curricular adjustments have been evaluated to understand the impact the changes have had on student development of scientific reasoning abilities.
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Historically, physics labs have been taught using what is termed the traditional method; that is, students are given step-by-step instructions on how to perform the lab and analyze data. This style was developed out of a need to assist students who have not yet developed advanced laboratory skills. Ricardo Trumper (Trumper, 2003) explains these ‘cookbook’ style experiments have students directly replicate what is given to them in the lab instructions, and subsequently they are expected to get specific results which are also provided for them. The idea is that students will learn good laboratory techniques through this mimicking behavior. A consequence of this approach, however, is student inability to make sense of the collected data and draw valid evidence-based conclusions. In addition, because students are given such direct guidance, these experiments do not peak student interest or promote ownership for their learning. Laboratory activities with complicated sets of procedures often turn students off and make it difficult for them to separate out the physics concepts. This type of guidance then leads to students not being able to express what physics they are testing or adequately communicate the implications of their results; or frustrates students such that they don’t care about working in the laboratory.

In 1993, Arons (Arons, 1993) addressed some of these issues by providing guidance for instruction in the laboratory which engages students and presents a different approach to learning science, such as having students engage directly in the decision making; such as how to use the equipment at hand to conduct an investigation, determine the number of measurements that need to be taken, how to discriminate between an observation and an inference along with how to manage data, how to interpret the experimental results, and how to engage in general
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hypothesised-deductive reasoning in connection with the laboratory practice. Arons approach allows students to build on their knowledge by encouraging students to think critically about the laboratory process and scientifically reason through their results.

In recent years, various studies have tried to alter this historical course and utilize some of Arons’ guidelines to determine a better method for physics instructors to enhance student learning.

- Corinne Zimmerman (Zimmerman, 2005) has done extensive research on the need for increased reasoning skills to be included in science courses. Though her main focus was on elementary and middle school students (with a minor focus on college age students), her approach is relevant to higher education. Zimmerman promoted the integration of reasoning skills into experimental design by using a scaffolding approach which allows instructors to not only provide a means for students to build their skills over the course of a term, but to target specific abilities, such as observations, reasoning and inferences.

- Eugenia Etkina developed the ISLE laboratories, so students can “Think Like a Scientist” (Etkina, 2006). Etkina’s curriculum engages students in real-life science processes such that students design experiments, engage in hypothesis testing, and make predictions through the use of guided questions. Her results showed gains in transferable skills such as student ability to effectively engage in experimental design (including ability to identify and control variables), make valid predictions and engage in hypothesis testing as evidenced by student reports submitted over the course of one semester. In a later study (Karelina and Etkina, 2007) gains were shown in scores from students using the ISLE laboratory procedures in their discussions to plan experiments, evaluate results, validate assumptions and make changes in their designs, if necessary.
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- Lei Bao (Bao, L., Cai, T., Koenig, K, et al, 2009) studied students in the US and China using multiple quantitative assessment instruments to evaluate concept learning in relation to scientific reasoning abilities. Although students in China engaged in more STEM high school coursework and outperformed their US counterparts on concept surveys, no differences in scientific abilities were noted. Bao et al. verified there is a need for ‘deep understanding of science reasoning’ instead of mere content recall; noting that the current style of teaching is not effective in student development of scientific reasoning abilities.

- Coletta and Phillips (Coletta and Phillips, 2010) developed a program called Thinking in Physics (TIP), an interactive method of teaching mechanics at the high school and college levels which includes a laboratory component. TIP includes group work (2-4 students) and introduces how to identify variables, determine their meaning and relevant relationships through active participation and discussions. A study investigating the impact of the curriculum resulted in a correlation of Force Concept Inventory (FCI) gains with improvements in scientific reasoning skills and problem-solving abilities as measured by the Lawson Classroom Test of Scientific Reasoning.

Additionally, in a recent report from the National Research Council, America’s Lab Report (Singer R., 2006), the claim is made that “achieving the goal of scientific literacy for all students, as well as motivating some students to study further in science, may require diverse approaches for the increasingly diverse body of science students.” In addition, it is reported that secure, well-paying jobs “require abilities that may be developed in science laboratories. These include the ability to use inductive and deductive reasoning to arrive at valid conclusions;
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distinguish among facts and opinions; identify false premises in an argument; and use mathematics to solve problems (Achieve, 2004).” The NRC calls for lab experiences that support students in attaining (1) mastery of subject matter, (2) development of scientific reasoning, (3) an understanding of the complexity and ambiguity of empirical work, (4) development of practical skills, (5) understanding of the nature of science, (6) a cultivation of interest in science and in learning science, and (7) development of teamwork abilities.

The studies and report described here indicate that the direction of physics laboratory curriculum must be shifted away from the traditional ‘cookbook’ style experiment instruction. In order for students to become our future scientists or become well prepared for a 21st century workforce, it is imperative to develop and implement new lab teaching methods which engage students and provide them with the appropriate scientific reasoning abilities. This masters research project, therefore, attempts to build upon the current research literature while better aligning the University of Cincinnati’s introductory physics laboratory courses with these new lab teaching methods that explicitly target transferable scientific abilities.

Chapter 2
Background

Traditional lab format

For many years students enrolled in the Introductory Physics laboratory course at the University of Cincinnati (UC) performed standard introductory physics experiments in a traditional format (see Appendix A). This format is content driven and may be described as more of a cookbook-type lab; i.e. it is heavily guided such that students are provided step-by-step instructions throughout the entire lab experiment. In addition, students are supplied with the
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exact lab equipment necessary to conduct the equipment along with an excel file that is specific to the lab activity and just needs to be filled in by the students. Both of these do not enable students to make decisions on their own; rather they must rely on what is provided to them for all data collection and analysis. This practice has not been shown to promote students to learn how to make experimental observations or think independently about analytical determinations (Arons, 1993).

The traditional lab course is also set up such that it is front-loaded. That is, students are given everything they are expected to use in the lab course during the first two weeks of the quarter. This includes measured uncertainties, propagation of uncertainties, random and systematic uncertainties, standard deviations and standard error, histograms and normal distributions, repeatability, accuracy, precision, scale limited error, standard equivalency Test, least squares fit, details of using, formatting and graphing in Excel (for example LINEST, fit lines, and error bars). Appendix B shows a comparison of how scientific processes are taught in the traditional and SR-focused labs. In addition, although the traditional method engages students in elements of the scientific process, it is done implicitly with the expectation that students will follow the strict guidelines and pick up on the process through implicit means. As discussed in chapter 1, the research is clear that this is not likely to occur (Trumper, 2003, Arons, 1993). Additionally, students are not held accountable for many of the scientific processes encountered in the lab course as they are not expected to discuss them in their final lab reports.

Scientific Reasoning-Focused format

On the other hand, the Scientific Reasoning-focused (SR-focused) lab curriculum was a redesign of the original more traditional curriculum such that it better aligns with the best teaching practices outlined in American’s Lab Report (2006) as described in chapter 1. In the
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SR-focused lab activities students become engaged in the entire laboratory process from the choice of hypothesis, design of the experiment, collection and analysis of data, and the drawing and communication of results (see Appendix C).

As the SR-focused curriculum was being developed, a number of aspects had to be considered prior to implementation: objectives of each lab activity, the physics concepts being tested, and the specific scientific processes to target each week such that students were not given too much up front.

In order to begin addressing deficiencies in the traditionally taught experiments, objectives for each experiment had to be determined. Many universities either don’t provide a set of objectives for their lab courses or the list is inadequate, such as only indicating that students should be able to verify a specific equation during the lab experience and therefore understand its origin. The objectives for the SR-focused curriculum were written to include both physics concepts as well as the development of specific scientific reasoning abilities.

Although the research literature promotes lab activities that put the responsibility for learning more directly on the student, such as those described in chapter 1, a completely new approach to altering the laboratory experience was not possible for this study. For example, due to the large number of students needing the experimental equipment provided in the labs, the choice was made to use the same equipment in the SR-focused labs as that which was provided for students in the more traditional lab sections. In addition, all lab students were in the same lecture course so deviating from the traditional lab topics was not deemed appropriate. And last, to be fair across all lab sections, both the traditional and SR-focused lab students took the same laboratory quizzes each week so adhering to similar lab topics was essential. The literature (Etkina, Karelina and Ruibal-Vilasenor, 2008) indicates that it takes more than 4 sequential
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experiments to instill changes in student scientific reasoning; therefore the SR-focused curriculum was designed for all 8 experiments completed during the quarter.

**Details.**

There are a number of aspects of the laboratory experience that had to be considered when updating the teaching design:

- Lab Class Design
- Experimental Background information provided to students
- Experiment Instructions provided to students
- Scaffolding of scientific processes provided to TAs
- Laboratory Reports

**Lab Class Design.**

The SR-focused laboratories performed the same eight experiments with the same equipment as the traditionally taught labs. In the initial study, the design and equipment followed closely with what the students did in the traditional labs. The big difference between the labs, however, was that in the SR-focused labs students worked in groups of 3-5 students instead of pairs. Instead of using step-by-step instructions to perform the experiment and analysis, each group discussed a series of questions to understand the physics background and how to identify variables, determine a testable hypothesis and create a design that would provide adequate results to answer the research questions. However, when results from the initial study indicated students did not develop significant shifts in the ability domains as expected, the SR-focused lab curriculum was redesigned to include a more targeted approach to teaching scientific reasoning abilities, streamline the document and remove redundant questions. Although the redesigned method in the second study performed the same experiments and used the same equipment, it
became apparent that students needed to be provided with more equipment than necessary due to the different experimental designs each group developed. When groups were provided with only the exact equipment to conduct an experiment a certain way, then all groups were observed to come up with identical hypotheses followed by identical experimental designs. This practice did not allow for creativity or the sharing of diverse approaches and is also promoted the idea that there is a single way to engage in scientific practices in the lab.

The SR-focused teaching method was designed to follow the recent literature (Coletta and Phillips, 2010) indicating that groups of students working toward a common goal was more effective for student learning than working in pairs. Therefore, each SR-focused lab class was divided into groups of 3 or 4 students instead of the traditional method of working in pairs. Students were encouraged to ‘switch jobs’ each week so all students had the opportunity to experience each aspect of laboratory practices. This allowed for discussion of the experimental procedures and a sense of collaboration. The structure of the activities within the lab class itself was also altered such that more whole class discussions took place at various points within the lab activity, such that students could share experimental designs, data, and results with the rest of the class.

*Experimental Background Information provided to students.*

Initially a set of objectives were written to reflect each experiment to be performed. The next step was to determine what background information (physics content) was necessary to provide to students. Since the lab curriculum is similar to the lecture curriculum, a lengthy background on physics content was not deemed necessary. Therefore, the background information provided was a brief overview of the concepts required for students to know for the experiment. A section in the background information provided a list of other topics students should review.
Experiment Instructions Information provided to students.

In order for students to be engaged in the SR-focused laboratory experience, each lab began with a discussion of the background information. This is different from the traditional teaching in that the Teaching Assistant (TA) does not just lecture to the class using a set of slides. In this new method, a concept is presented by the TA and students are then asked questions to provide additional details about what might be tested in the experiment, held constant, etc; all the while encouraging the whole class to participate in the discussion. Once students break into their groups, the SR-focused curriculum guides students through a series of questions about the basic physics involved in the experiment as well as the procedures they will use to collect and analyze data. In the Spring study this part of the lab activity became more open-ended for the students and was less guided to promote decision-making.

As part of the experimental instructions, students are prompted to identify variables, determine research questions to be addressed and determine the best experimental design to collect enough useable data to test their hypothesis. Students used an Experiment Information Sheet to document their variables, hypothesis, prediction, experimental design and observations. The traditional lab included a data sheet which included collected data with observations and a drawing of the experimental set-up, but the information sheet for the SR-focused labs went a step further and required students to write down their hypothesis, all variables, experimental design in addition to observations and data collected.

Once data has been collected, the TA leads a whole class discussion on how best to analyze the data. At the beginning of the quarter, basic equations and variable relationships were provided for students as scaffolding so they would learn what was expected of them. As the quarter progressed, students were either provided minimal or no guidance to perform their data
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analysis. This is different from the traditional lab instructions in which students were always provided with step-by-step instructions on what data to collect, which variables to compare, what equations and graphs should be included in the data analysis, and so on.

At the end of each lab class, students finalize their discussions by determining how to improve their experiment and the entire class discusses how the physics might be used in a real life situation.

A copy of the student and TA experimental instructions for the SR-focused labs can be found in Appendices C (initial study) and D (second study), and the traditional experimental instructions may be found in Appendix E.

**Scaffolding of scientific processes provided to TAs.**

Since many students are taking a physics lab for the first time (see demographics section), it is essential to include information concerning basic research terminology and processes in the laboratory instructions. To incorporate this into the SR-focused lab setting, a scaffolding approach was used. This approach allowed certain aspects of scientific reasoning skills to be taught as the quarter progressed instead of all at the beginning of the quarter as is the procedure used in the traditionally taught labs (see Appendix B). By teaching only a few new skills or scientific processes each week, students are better able to focus on these specific abilities and the physics involved. This approach provides students with a solid foundation and incorporates previous targeted knowledge into new processes taught during the current experiment.

For example, writing a formal hypothesis is taught during the 5th experiment. In the labs leading up to this experiment, students learn how to write a research question, identify variables and make predictions about their results. This scaffolding provides a logical transfer of their previous knowledge to the new concept.
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For example, the scaffolding approach is useful when teaching uncertainties in the introductory physics laboratory. This can be a difficult concept for students to comprehend. In the traditional method, students are generally expected to learn what an uncertainty is, be able to calculate them and use them in analysis, all in the first two labs. Students in the traditional labs follow the step-by-step instructions on what calculations to perform, but often don’t understand from where uncertainties are developed or how to appropriately include them in their discussion of the analysis. The SR-focused method separates uncertainties into a series of learning events. Initially students are taught the concept of uncertainty – what it means and how to obtain measured uncertainties. Throughout the quarter, students learn why uncertainties are important, how to calculate them and why they are used to present experimental results.

Laboratory Reports.

Although student lab report submissions vary among universities, many follow a standardized approach that parallels the scientific method. As part of the SR-focused method of lab teaching, the focus of the lab reports was redirected to include not only the physics of the experiments but the appropriate use of scientific abilities as well with particular emphasis on student ability to present evidence-based conclusions. The more traditional lab reports at UC place a large emphasis on calculations, uncertainties, and presentation of data. While each of these is important, the SR-focused lab reports are assessed with a detailed scoring rubric that focuses on the following:

- Identification of research question/hypothesis
- Designing a reliable experiment that tests the hypothesis
- Identification of variables
- Identification of assumptions and how they may affect results
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- Communication of design details
- Presentation of data in multiple forms
- Identification of patterns/trends in the data
- Ability to make a prediction based on the hypothesis
- Ability to make a reasonable claim which supports or refutes the hypothesis and is supported by experimental evidence
- Discussion of results which includes comparisons of results with known values, how errors and assumptions impact results
- Identification of short-comings in experimental design and suggestions for improvements
- Simple application of physics concepts

As new concepts are introduced in the lab course, they are incorporated into the subsequent lab reports. (see Appendix F for a copy of the lab report guidelines)

Initially, grading of the SR-focused course lab reports was more in line with what was required on the traditional lab course grading rubric. The evaluation was primarily on the concepts and abilities emphasized in the lab classes. When re-evaluating the SR-focused course for the second study, the researchers determined that the lab report guidelines and subsequent grading rubric should be expanded to encompass all the abilities being taught as part of the scaffolding. This expanded rubric also provided an avenue for direct feedback to students on what they were lacking in their reports.

A sample of the grading rubric may be found in Appendix G.
Chapter 3

Methods of Investigation

Population and Setting

The study was conducted with students enrolled in the first introductory physics lab during two different quarters at the University of Cincinnati. The initial study included students enrolled in the algebra-based introductory physics laboratory course during Winter Quarter 2012 at the University of Cincinnati (UC). There were a total of 6 laboratory sections included: 3 were taught using the step-by-step instruction method (identified as traditional in this thesis) and 3 were taught with the scientific reasoning-focused (identified as SR-focused) method. A total of 54 students were enrolled in the study; 20 in the traditional and 34 in the SR-focused method. There were a total of 3 graduate student teaching assistants (TAs) who taught these sections; one is the researcher for this study and two are seasoned TAs. Each TA taught one traditional and one SR-focused method lab section.

The second subsequent study included students enrolled in the calculus-based introductory physics laboratory course during Spring Quarter 2012 at UC. There were a total of 3 laboratory sections as part of this course, with a total of 49 students enrolled. All three sections were taught using the SR-focused method by one TA; the researcher for this study.

In both the initial and second study, all laboratory classes at (UC) were taught independently from the lecture classes in specified laboratory rooms. Laboratory class enrollments ranged from 16 to 22 students.
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**Student background.**

While a majority of the students previously took physics in high school (59.02% in the algebra-based SR-focused, 62.50% in the algebra-based traditional and 89.80% in the calculus-based SR-focused), only 40% of each of these groups felt they were adequately prepared for college physics according to a student survey administered by the researcher. Additionally, 22% of the students in the calculus-based course felt they were *very* well prepared for college physics.

Students in both these courses tend to have taken other math and science courses as part of their majors. The majority of the algebra-based students have taken Calculus 1 (28.57% for SR-focused and 42.86% for traditional) and Calculus 2 (23.81% for SR-focused and 19.05% for traditional) as their highest and only mathematics courses. Also, these students generally took the introductory biology and chemistry laboratory courses (38.10% SR-focused /28.57 traditional and 61.90% SR-focused /47.62% traditional, respectively) with approximately 1/3 of the students taking higher levels of biology, chemistry and anatomy. When the data for students in the calculus-based course are evaluated, it is noted that 34.69% have taken Calculus 2 and 32.65% have taken Calculus 3. This group of students also took a variety of other science laboratory courses: 46.94% have taken Chemistry, 6.12% have taken Biology and 10.20% were concurrently taking the Physics 2 laboratory.

It is important to note the introductory Biology laboratory course at the University of Cincinnati is taught using an inquiry method that is quite different from what is considered traditional biology lab activities. In these inquiry-based biology labs the students work in groups of 3-4 and engage in exploratory activities before developing their own hypotheses to test. The group determines their own experimental designs, collect and analyze all data, and write up an abstract and brief journal-type article on the activity rather than the more traditional lab report.
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The alternative lab curriculum implemented in this study is based on a similar approach, so students who have taken the biology lab sequence may better understand the reasoning process involved in this type of inquiry over those who haven’t taken introductory Biology lab. The introductory chemistry course is taught in the traditional manner; therefore, there should be no direct effect from those students who have taken the introductory chemistry series.

Students were also surveyed to collect their intended major and grade level. The following graphs shown in Figure 3.1 indicate the majority of students were Health Sciences and Mechanical Engineering Technology (algebra-based SR-focused), Construction Management and Mechanical Engineering Technology (algebra-based traditional) and Engineering (Architectural, Computer Science, Electrical, Aerospace and Mechanical) in the calculus-based SR-focused course.

Figure 3.1. Graphs indicating majors of students.
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The majority of students in the algebra-based traditional and calculus-based SR-focused labs were freshmen, while the grade levels of freshman, sophomore and junior were equally represented in the algebra-based SR-focused course.

Figure 3.2. Graph indicating grade level

Scientific Reasoning Skills

Over the course of the revised lab curriculum students developed specific scientific reasoning abilities through carefully designed activities. Students were expected to practice these abilities in each lab investigation and then incorporate what they learned into their lab reports. In particular, the curricular focus was on developing students’ abilities in developing and testing hypotheses, identifying and controlling variables, understanding relationships between variables (i.e. correlational thinking), deductive reasoning. Emphases on science and engineering practices such as defined by *A Framework for K-12 Science Education* (NRC, 2012) were also employed including formulating a testable hypothesis, designing an appropriate
experiment to provide appropriate data to answer the hypothesis, analyzing experimental data and using evidence to support argumentation in experimental evaluation and conclusions.

In order to assess student acquisition of scientific reasoning skills, Lawson’s Test of Scientific Reasoning was administered as a pre- and post-test for the course and an evaluation of students’ written lab reports was conducted using scoring rubrics.

**Lawson’s Classroom Test of Scientific Reasoning.**

Lawson’s Classroom Test of Scientific Reasoning (LCTSR) is research validated test that involves 24 multiple choice questions (Lawson, 1978, 2000). It is commonly used in research studies due to its ease of administration (i.e. paper and pencil test). It was chosen for this study because it is a solid evaluation tool for assessing scientific reasoning skills and may be used as a baseline when other forms of evaluation are used in conjunction with the test. The LCTSR assesses scientific reasoning abilities under six domains including conservation of matter and volume, proportional reasoning, identification and control of variables, probabilistic reasoning, correlational thinking, and hypothetical-deductive reasoning.

As part of this study, the LCTSR was given as a paper and pencil pre-test prior to students performing the first lab investigation of the course and as a post-test immediately after completion of the last lab investigation. For students not enrolled in lab during Spring 2012 (PHYS 201, lecture only), the LCTSR was given during the first week and last week of the quarter via Blackboard. Student pre- and post-test responses were placed into an Excel file and matched by student. Any student that did not complete the LCTSR as a pre- or post-test was removed from the study. A paired two-tailed t-test was conducted for the total LCTSR score as well as each of the six domains assessed by the test.
Assessment of lab reports for reasoning skills.

As part of the lab course students were required to write weekly lab reports; one for each lab investigation. As previously discussed, the lab report template and grading system for the initial study were similar to the traditionally taught lab course with a slightly different focus toward scientific reasoning. In reassessing materials for the second study, the lab report template and grading rubric were upgraded to better align the lab report requirements with the course objectives (see copy of lab report guidelines in Appendix F). Additionally, as new scientific processes were taught throughout the term, students were expected to incorporate this new knowledge into their lab reports.

In order to strengthen this study, several areas from the lab reports were assessed using scoring rubrics to determine student level of proficiency in these areas. These included students’ ability to identify and control of variables, discuss assumptions and predictions in relation to their hypotheses, and engage in argumentation regarding whether their claims were supported or refuted as well as present their reasoning through a logical conclusion of their experiment. Since the SR-focused lab curriculum in the second study better targeted these particular skills, only lab reports from the second study were reviewed for analysis.

Identification and control of variables.

To assess identification and control of variables, individual lab reports were evaluated to determine whether students correctly identified the independent, dependent and controlled variables. Each assessed lab report was scored using a rubric which was designed by the researchers that defined the level to which students were able to employ this reasoning ability.

The scoring rubric, as shown in Appendix H, was used to evaluate how well students were able to identify variables. For independent and dependent variables, a simple comparison
was made between “none or incorrect” and “correct identification”. The “none or incorrect” was assigned a value of zero (0) and “correct” was assign a value of one (1). For the “none or incorrect” category, subcategories of none, confused with independent variable (IV), confused with dependent variable (DV) and confused with controlled variable (COV) were noted as needed. For control of variables, a rubric with a three value system (0, 1, 2) was used: none or incorrect (0), obviously controlled variables in the experiment (1) and other considerations made by the student to include additional control of variables and assumptions (2). Similar to the IV and DV category, the “none or incorrect” category was subcategorized into none, confused with IV, confused with DV.

To better evaluate student ability to identify and control variables, students’ inclusion of multiple controlled variables, assumptions and how the assumptions affect results were considered. Lab reports from two experiments were scored by the researcher: the 3rd experiment, Falling Bodies, which was the experiment after the concept of variables was introduced and the 6th lab, Centripetal Forces, the lab which taught the final scientific process. By comparing rubric scores from these two experiments, shifts in students’ ability to identify and control variables, along with their understanding of what affects experimental results could be identified.

**Writing a Hypothesis and Including Assumptions.**

Students were taught the basics of writing a hypothesis during the second experiment and learned how to develop a prediction based on their hypothesis for the experiment during the falling bodies experiment (third experiment). As part of the instruction for the centripetal forces lab, emphasis was placed on how assumptions and uncertainties affected the performance and results of the experiment. Therefore, the falling bodies lab reports were used as a baseline of
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these scientific skills and the centripetal forces lab reports provided an adequate comparison, since students had ample opportunities to practice writing hypothesis and predictions and incorporate this information into their lab reports.

The ISLE Testing Experiment Rubric (Etkina, 2006) developed by Eugenia Etkina was used by the researcher to evaluate students’ ability to write a testable hypothesis, make a prediction, identify assumptions and make a reasonable judgment about the hypothesis through their experimental design. This rubric includes a total of 9 categories with each being rated on a scale of 0 to 3. The complete rubric may be viewed in Appendix H.

Argumentation.

As with the previous two sections, individual student lab report reports were assessed by the researcher using scoring rubrics to determine whether students gain the skills necessary to present an adequate and correct argument which includes appropriate evidence to support experimental conclusions. The Falling Bodies lab reports were compared with the lab reports from the seventh experiment, Momentum and Energy. The Falling Bodies lab report was chosen because this was the first lab report which incorporated all aspects of a proper conclusion. The Momentum and Energy lab report was chosen because all targeted scientific abilities had been taught prior to this experiment. Students were expected to write a robust lab report for the final two experiments with an emphasis on experimental design and reasoning through results.

For the analysis, a rubric was created by combining the NSTA’s Rubric for argumentation (Sampson, 2004) with two categories from the ISLE Data Analysis Rubric (Etkina, 2006). The Sampson Rubric measures student ability to make a sufficient and accurate claim, provide genuine and sufficient evidence to support that claim, and provide adequate rationale to explain why the evidence supports the claim. The categories selected from the Data
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Analysis Rubric target identification of uncertainties, determination of shortcomings of the experiment and suggestions for improvement in the experimental design. This rubric includes a total of 7 categories to be assessed with each being rated on a scale of 0 to 3. The complete rubric can be found in Appendix H.

For all scoring rubrics, individual student lab scores for each rubric item were placed into an Excel file and matched by student across the two labs under evaluation. Any student that did not complete one of the two labs was removed from the analysis. A paired two-tailed t-test was conducted for each to determine if shifts in rubric scores were significant.

Student Response to Labs

Two approaches were taken to address the second research question “How do students respond to the lab experience”. Opinions of the students were sought in response to their participation in laboratory course by a survey and researchers evaluated how students performed in the laboratory as perceived by the TAs.

Student Survey

Students in both the initial study and the second study were provided anonymous surveys, developed by the researcher, to complete at the end of the respective courses (see Appendix I for full survey). The survey contained questions to obtain student demographic information (such as math preparation, previous laboratory experience and intended major) along with opinions from students regarding their lab experience. In particular, questions centered on how the current laboratory experience impacted their learning in the lecture course. The survey included 7 open-ended questions to determine what aspects of the lab investigations were useful or needed improvement and how the lab experience prepared them for lecture. A series of 8 Likert-scale questions were used to determine if students received feedback on their physics knowledge,
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whether the laboratory experience enhanced learning in the lecture and recitation portions of the course and evaluate student preferences for learning within a laboratory setting. For example, students were asked to rate on a scale of 1 (helped) to 5 (no help), the statement “Physics lab helped me think more deeply about course materials”.

The survey responses were first aggregated by individual lab sections to determine if large differences in perceived lab experience were evident between sections as these were taught by three different TAs. Survey data was later aggregated according to 3 comparison groups for final analysis (Initial study: traditional and SR-focused; Second study: SR-focused). This allowed for the determination of differences in student views of the lab experience between the traditionally taught and SR-focused method as well as differences from the initial to second study.

**TA Perspective**

During the initial study, the TAs were provided with the appropriate instructions for each section (traditional or SR-focused). TAs who taught the SR-focused lab sections were provided background information and experiment instructions, including the scaffolding outline and prompts to assist students. In the SR-focused labs, this information allowed each TA to directly interact with the groups of students, since the structure of the SR-focused method included whole-class and group discussions. Interacting with students provided a link for TAs to determine students’ understanding of concepts, scientific abilities and communication skills. And finally, each TA graded their own SR-focused sections’ lab reports. Therefore, TAs could quickly assess students’ communication of concepts, analysis and reasoning through their decisions.
Guidelines for the traditionally taught labs were provided to the TAs by the UC Laboratory Director as is normally done for this lab course. The guidelines include a written document which incorporates basic physics concepts into the step-by-step laboratory instructions, which are also provided to the students. The UC Laboratory Director holds laboratory information sessions every other week during the academic quarter to explain each experiment in detail to the TAs. As students are required to follow the detailed instruction manual, they only interact with the TA if they have a question regarding how to perform a task. The lab reports for the traditionally taught experiments were distributed randomly among all TAs teaching the introductory physics laboratories and therefore, the TAs assisting the researcher by teaching the traditional labs, did not have direct access to their students’ performance on the lab reports.

Three graduate student teaching assistants (TAs) taught the six laboratory sections in the initial study: one was the researcher and two were seasoned TAs. Each TA taught one traditional and one SR-focused lab section. The two seasoned TAs were provided with details of the research study prior to the beginning of Winter Quarter 2012. Weekly discussions occurred between the TAs and the researcher either in person or via email to clarify any questions regarding the concept questions students were required to answer or the scientific abilities to be taught each week through scaffolded activities. The TAs who taught during the initial study were interviewed at the end of the term using an interview protocol developed by the researcher (see Appendix J) to collect information regarding their views of students’ response to the laboratory experience. The interviews were held individually in the researcher’s physics graduate office at UC. Each interview lasted approximately 20 minutes. Both TAs were provided with the list of questions in advance of the interview to allow time to reflect upon their
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own experience teaching the labs. During the interview the researcher asked each question and allowed the TA sufficient time to answer in an open-ended format. Both interviews were audio-taped with permission of each TA. The researcher later listed to the taped interviews to summarized key comments of the TAs’ perspectives from each question for analysis. A full transcript was not written of either interview. This provided the researcher with feedback as to the success and shortcomings of each experiment as they occurred and through a formal interview at the conclusion of the academic quarter.

For the second study, there were a total of 3 laboratory sections all taught using the SR-focused method by one TA, the researcher. Therefore no feedback from other TAs was collected. However, the researcher made notes during each experiment to indicate which aspects were successful and which needed improvements.

Chapter 4

Evaluation and Results

In this chapter data are presented to address two research questions including (1) How does the SR-focused lab curriculum impact development of student scientific reasoning abilities?” and (2) “How do students respond to the reformed lab experience?”. The data was collected using a variety of instruments including the Lawson Classroom Test of Scientific Reasoning, lab report scoring rubrics, student course evaluations/surveys, and interviews with teaching assistants. This chapter is organized according to the research question being addressed followed by what aspect of the question is being targeted.
Impact of SR-focused lab curriculum on scientific reasoning abilities

This section presents data on how the SR-focused laboratory curriculum impacted students’ scientific reasoning abilities. There are two major tools used in this study: the Lawson Classroom Test of Scientific Reasoning (LCTSR) and a lab report analysis using rubrics. The analysis of the LCTSR data involves three comparisons of data to determine existence of significant gains in student performance including:

- Paired pre- and post-test analysis by total score
- Paired pre- and post-test score by ability domain

Similarly, the lab report scoring rubrics utilized in this study involve three specific ability domains including:

- Identification and control of variables
- Testing hypotheses, making valid predictions and assumptions
- Engagement in argumentation

**Lawson Classroom Test of Scientific Reasoning: Paired pre- and post-test analysis.**

The Lawson Test assesses student’s scientific reasoning abilities in six domains: conservation of mass and volume, proportional reasoning, ability to identify and control of variables, probabilistic reasoning, correlational thinking and hypothetico-deductive reasoning. The pre- and post-test scores of students were compared to evaluate any differences in acquisition of these abilities in several specific settings:

- Initial study Winter 2012: scores of students in the traditionally taught lab sections were compared with those in the SR-focused taught lab sections (PHYS 101)
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- Second study Spring 2012: scores of students in the SR-focused lab sections were compared with those of students who were only enrolled in the corresponding lecture (PHYS 201)
  - Subsections of these comparison groups were also evaluated:
    - Students in lecture but not in laboratory course
    - Students in the laboratory course regardless of lecture status

**Lawson Classroom Test of Scientific Reasoning: Total Score.**

The results in Table 4.1 show a significant increase in total pre- to post-Lawson scores in all SR-focused lab sections with no significant shift in the traditional lab sections. This finding supports what has been reported in the research literature as well as that observed by Koenig (see Table 4.2). That is, the more traditional courses and lab curriculum that do not *explicitly* target student scientific reasoning abilities do not result in significant shifts in student abilities in these areas. On the other hand, courses that explicitly engage students in activities that practice these abilities and include related assessments, do see significant shifts in student scientific reasoning abilities (see Table 4.2) (Koenig et al., 2012).

**Table 4.1.** Pre- and Post-Lawson scores for PHYS 101 and PHYS 201 students at UC

<table>
<thead>
<tr>
<th></th>
<th>Pre-Test Score (of 24)</th>
<th>Post-Test Score (of 24)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Study Winter 2012</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(PHYS 101) Traditional</td>
<td>n = 20</td>
<td>15.75 (66%)</td>
<td>15.25 (64%)</td>
</tr>
<tr>
<td><strong>Initial Study Winter 2012</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(PHYS 101) SR-focused</td>
<td>n = 34</td>
<td>16.68 (69%)</td>
<td>17.91 (75%)</td>
</tr>
<tr>
<td><strong>Spring 2012</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lecture Only (PHYS 201)</td>
<td>n = 63</td>
<td>19.00 (79%)</td>
<td>19.78 (82%)</td>
</tr>
<tr>
<td><strong>Second Study Spring 2012</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-focused Lab (PHYS 201)</td>
<td>n = 49</td>
<td>18.51 (77%)</td>
<td>20.08 (84%)</td>
</tr>
</tbody>
</table>
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Table 4.2. Pre- and Post-Lawson scores for students in multiple courses at Wright State*

<table>
<thead>
<tr>
<th>Courses</th>
<th>n</th>
<th>Pre-Lawson</th>
<th>Post-Lawson</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional lab instruction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIO 111 (take alg-based physics)</td>
<td>144</td>
<td>13.56 (57%)</td>
<td>14.00 (58%)</td>
<td>p &gt; 0.05</td>
</tr>
<tr>
<td>PHY 107 (non-science major)</td>
<td>91</td>
<td>15.36</td>
<td>16.51</td>
<td>p &gt; 0.05</td>
</tr>
<tr>
<td>PHY 244 (calc-based)</td>
<td>62</td>
<td>18.91</td>
<td>19.85</td>
<td>p &gt; 0.05</td>
</tr>
<tr>
<td>Scientific reasoning-targeted instruction</td>
<td>SM 145 (pre-service teachers)</td>
<td>59</td>
<td>14.3 (60%)</td>
<td>17.3 (72%)</td>
</tr>
</tbody>
</table>

*collected by Kathy Koenig during fall quarters 2007 and 2010

Lawson Classroom Test of Scientific Reasoning: Score by Ability Domain.

Although it is beneficial to see significant shifts in total scores to demonstrate that students are acquiring scientific reasoning abilities, there are six different ability domains assessed within the Lawson test. To determine which of the abilities the highest gains were obtained, paired two-tail t-Tests were conducted for student pre- and post-test scores for each domain (see Table 4.3).
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Table 4.3. Student pre- and post-test scores for each ability domain on the Lawson test

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Traditional Lab (PHYS 101)</td>
<td>SR-Focused Lab (PHYS 101)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>n = 20</td>
<td>n = 34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>Conservation</td>
<td>3.55 (89%)</td>
<td>3.50 (88%)</td>
<td>3.76 (94%)</td>
<td>3.71 (93%)</td>
</tr>
<tr>
<td></td>
<td>(84%)</td>
<td>(89%)</td>
<td>(91%)</td>
<td>(93%)</td>
</tr>
<tr>
<td>Proportional</td>
<td>1.80 (45%)</td>
<td>2.06 (51%)</td>
<td>2.92 (73%)</td>
<td>2.76 (69%)</td>
</tr>
<tr>
<td>Reasoning</td>
<td>(53%)</td>
<td>(61%)</td>
<td>(83%)</td>
<td>(78%)</td>
</tr>
<tr>
<td>Control</td>
<td>3.55 (59%)</td>
<td>3.82 (64%)</td>
<td>4.06 (68%)</td>
<td>4.00 (67%)</td>
</tr>
<tr>
<td>Variables</td>
<td>(49%)</td>
<td>(64%)</td>
<td>(74%)</td>
<td>(80%)</td>
</tr>
<tr>
<td>Probabilistic</td>
<td>3.50 (88%)</td>
<td>3.65 (91%)</td>
<td>3.84 (96%)</td>
<td>3.92 (98%)</td>
</tr>
<tr>
<td>Reasoning</td>
<td>(85%)</td>
<td>(95%)</td>
<td>(96%)</td>
<td>(96%)</td>
</tr>
<tr>
<td>Correlational</td>
<td>1.45 (73%)</td>
<td>1.38 (69%)</td>
<td>1.67 (83%)</td>
<td>1.71 (86%)</td>
</tr>
<tr>
<td>Thinking</td>
<td>(80%)</td>
<td>(86%)</td>
<td>(89%)</td>
<td>(94%)</td>
</tr>
<tr>
<td>Hypothetico-</td>
<td>1.90 (48%)</td>
<td>2.26 (57%)</td>
<td>2.75 (69%)</td>
<td>2.41 (60%)</td>
</tr>
<tr>
<td>Deductive</td>
<td>(46%)</td>
<td>(64%)</td>
<td>(68%)</td>
<td>(67%)</td>
</tr>
<tr>
<td>Reasoning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pre value</td>
<td>0.214</td>
<td>0.154</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pre value</td>
<td>0.748</td>
<td>1.000</td>
<td>0.859</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pre value</td>
<td>0.527</td>
<td>0.058</td>
<td>0.278</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pre value</td>
<td>0.878</td>
<td>0.119</td>
<td>0.928</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
*must have p < 0.004 to be significant due to Bonferroni Correction
**In the Spring study there was a comparison group of students (n=63) enrolled only in lecture with another group (n=49) enrolled in the SR-focused lab with 32 of these lab students also in lecture

The results for the SR-focused laboratory sections in Table 4.3 indicate there is a statistically significant gain in test scores for the control of variables domain (p = 0.001). This significant gain was expected as this was one of the abilities specifically targeted in this SR-focused laboratory instruction. That is, each group of students was expected to apply their understanding of how to determine relevant independent and dependent variables along with those that needed to be controlled (held constant) in each experiment. These choices then had to be communicated in the corresponding lab report.

The proportional reasoning and correlational thinking domains in the laboratory sections show moderate gains even though they cannot be considered significant due to the Bonferroni correction (p must be < 0.004 due to the Bonferroni correction). The lecture-only subsection indicates there is a moderate gain in the proportional reasoning domain. It is uncertain as to why
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does is the case but it could be due to the use of proportional reasoning with end-of-the-chapter problems in lecture.

**Lab Report Analysis: Ability to Identify and Control Variables.**

One of the reasoning skills targeted in the SR-focused method was proper identification of variables: independent, dependent and control. Although the LCTSR assessed this ability and showed significant gains in the control of variables domain, lab reports were analyzed using appropriate scoring rubrics to provide supporting information. In particular, in order to determine if any shift in student ability to identify these variables occurred across the quarter, lab reports for two experiments were analyzed: falling bodies (3rd experiment) and centripetal forces (6th experiment). In the first two weeks of the quarter students learned to identify variables and write relevant research questions. The falling bodies experiment was the first lab class in which students were expected to apply this knowledge creating their own experimental design, which included identifying the independent, dependent and controlled variables without direct assistance from the TA. Therefore, the lab reports from the fb experiment provide a good baseline for student ability to identify all variables. In the experiment just prior to the centripetal forces lab (that is, the 5th experiment, Newton’s Laws), emphasis was placed on controlling variables. Subsequently, the centripetal forces lab reports were used as a comparison to the earlier falling bodies lab report because students would have had adequate practice identifying variables and determining what variables needed to be controlled to develop a more robust testing design.

The rubrics, as shown in Appendix H, were used to evaluate how well students were able to identify variables. For independent and dependent variables, a simple comparison between none or incorrect was compared with correct identification. For the “none or incorrect” category,
subcategories of none, confused with independent variable (IV), confused with dependent variable (DV) and confused with controlled variable (COV) were noted as appropriate. For control of variables, a three tiered rubric was used: none or incorrect, obviously controlled variables in the experiment and other considerations made by the student to include additional control of variables and assumptions. Similar to the IV and DV category, the “none or incorrect” category was subcategorized into none, confused with IV, confused with DV.

Only lab reports of students who had completed both reports were analyzed (n=41, representing 80% of those who completed the course). A paired samples two-tail t-test was conducted to compare identification of independent, dependent and controlled variables in both the falling bodies and the centripetal forces lab reports. For independent and dependent variables, no statistically significant shift occurred. The mean rubric scores were initially high on the falling bodies lab report (mean$_{IV}$ = 0.88, var. = 0.10; mean$_{DV}$ = 0.88, var. = 0.90) so there was little room for significant improvement in this ability domain.

On the other hand, there was a significant difference in scores for the control of variables in the falling bodies (mean = 0.64, var. = 0.52) and centripetal forces (mean = 1.26, var. = 0.63); $t (41) = -5.49, p < 0.000$ lab reports. These results indicate advances in this ability domain as in the latter lab report students were able to appropriately identify more than just the obvious control variables and include assumptions nearly twice as often as in the former lab report. This significant shift in student abilities in the control of variables was also observed in the Lawson Test results (see pre- and post-Lawson test subsection above).

It should be noted that students were introduced to independent and dependent variables during the first experiment in Week 1 and each group of students was expected to identify these variables before they began collecting data for their experiments. Although students were
expected to also communicate which variables were controlled, early experiments did not lend themselves to this concept. The first two experiments were Measurement and Uncertainties and Data Graphics, both which utilized a basic pendulum for students to begin their learning in a laboratory. Since these experiments were very simple in nature, control of variables was discussed, but not emphasized. It was more important for the students to initially learn what data to collect and how to collect it. As observed in the falling bodies lab report, approximately 16% of the students initially confused the COV with the independent variable, while approximately 33% of the students initially didn’t include a COV at all as determined by the subcategories. These values dropped to 7% and 16% on the centripetal forces lab report. In addition, as the quarter progressed the concept of control of variables became more obvious to the students and it became an integral part of their work in lab. That is, the researcher noticed more frequent in-class discussions amongst students regarding the control of variables in their experimental designs and these discussions were initiated by the students themselves. Although a significant shift in student ability to identify and control variables was observed, students have not mastered this ability as indicated by the rubric scores and Lawson post-test scores. This finding is supported in the research literature in which students continue to struggle with this idea of controlling variables in the college setting (Lawson, A.E., Banks, D. L., and Logvin, M., 2006).

**Lab Report Analysis: Testable Hypothesis, Prediction and Assumptions.**

Each group of students was charged with applying the variables identified for the experiment into a testable hypothesis. Students then discussed how to design their experiment to test the hypothesis, taking into account any assumptions or constraints associated with the experiment. Students were expected to detail this information in their lab reports. Again, in order to determine any shifts in learning on these skills during the quarter, assessments of the
falling bodies and centripetal forces lab reports were completed. The falling bodies experiment, as stated previously is a good baseline to use for lab reports. Students were presented with new information regarding development of a prediction in relation to the hypothesis for the experiment during the falling bodies experiment. The centripetal forces experiment expected students to write a formal hypothesis and write their prediction with an emphasis on considering the effects of assumptions and uncertainties. Therefore, the cf lab reports provided a good comparison, since students had ample time to practice writing hypothesis and predictions and incorporate this information into their lab reports.

Eugenia Etkina’s ISLE Testing Experiment Rubric (Etkina, 2006) was used to evaluate students’ ability to write a testable hypothesis, make a prediction, identify assumptions and make a reasonable judgment about the hypothesis through their experimental design. This rubric includes a total of 9 categories with each being rated on a scale of 0 to 3. The complete rubric is in Appendix H.

Only lab reports of students who had completed both the falling bodies and centripetal forces reports were analyzed (n=41, representing 80% of those who completed the course). A paired samples two-tail t-test was conducted to compare each of the 9 categories found on the rubric.
Table 4.4. Paired sample t-Test scores for Hypothesis Testing, Predictions and Assumptions

<table>
<thead>
<tr>
<th>Scientific Ability</th>
<th>Experiment</th>
<th>Mean</th>
<th>Variance</th>
<th>t(df=41)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to identify the hypothesis to be tested</td>
<td>fb</td>
<td>2.76</td>
<td>0.52</td>
<td>-0.32</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>2.80</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to design a reliable experiment that tests the hypothesis</td>
<td>fb</td>
<td>2.88</td>
<td>0.25</td>
<td>0.00</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>2.88</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to distinguish between a hypothesis and a prediction</td>
<td>fb</td>
<td>1.21</td>
<td>0.66</td>
<td>-3.15</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>1.86</td>
<td>1.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to make a reasonable prediction based on a hypothesis</td>
<td>fb</td>
<td>1.55</td>
<td>0.74</td>
<td>-2.04</td>
<td>0.048</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>1.95</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to identify the assumptions made in making the prediction</td>
<td>fb</td>
<td>1.19</td>
<td>0.69</td>
<td>-3.11</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>1.69</td>
<td>0.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to determine specifically the way in which assumptions might affect the prediction</td>
<td>fb</td>
<td>1.05</td>
<td>0.77</td>
<td>-2.71</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>1.55</td>
<td>1.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to decide whether the prediction and the outcome agree/disagree</td>
<td>fb</td>
<td>1.64</td>
<td>0.77</td>
<td>-1.052</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>1.83</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to make a reasonable judgment about the hypothesis</td>
<td>fb</td>
<td>1.74</td>
<td>0.73</td>
<td>-1.35</td>
<td>0.186</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>1.93</td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to revise the hypothesis when necessary</td>
<td>fb</td>
<td>0.24</td>
<td>0.57</td>
<td>-1.92</td>
<td>0.062</td>
</tr>
<tr>
<td></td>
<td>cf</td>
<td>0.59</td>
<td>1.17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These results suggest that students improved upon their ability to adequately distinguish between a hypothesis and a prediction. The results also indicate a gain in students’ ability to identify assumptions associated with the experiments and in determining how the assumptions may affect their prediction. The other six categories on the rubric did not demonstrate significant improvement for the students. However, although not considered statistically significant, 45% of students were able to improve upon their ability to make a reasonable prediction based on their hypothesis and 19% of students demonstrated they were able to revise their hypothesis after determining its flaws in the latter experiment.

From the beginning of the laboratory course students were instructed on how to write a testable hypothesis. However, students were not instructed on writing scientifically valid
predictions until the third and fourth experiments (falling bodies and vector forces, respectively).
Therefore, the smaller gains observed in this ability were expected, since students did not have substantial practice prior to writing the falling bodies laboratory report. Similarly, identifying assumptions and constraints were both addressed from the beginning of the course and were practiced by students during each experiment. However, explaining in writing how assumptions might impact results and conclusions was not emphasized until the fifth and sixth experiments, i.e. Newton’s laws and centripetal forces, respectively.

**Lab Report Analysis: Argumentation.**

For each experiment, students were expected to write a lab report which summarized the experimental design, data and analysis, and conclusions made. As with any scientific report, students were required to evaluate their findings to determine if their hypotheses were supported or refuted, while taking into consideration assumptions and sources of experimental uncertainty. Students were expected to provide adequate evidence from their results to support any claims made. Students were also expected to evaluate the design of their investigation to determine shortcomings in experimental design and whether or not the experiment could be upgraded.

In order to determine any shifts in learning for this set of skills, a combination of two rubrics was used to do the assessment. The NSTA Sampson Rubric for argumentation (Sampson, 2004) was combined with two categories from Eugenia Etkina’s ISLE Data Analysis Rubric (Etkina, 2006). This rubric includes a total of 7 categories with each being rated on a scale of 0 to 3. The complete rubric can be found in Appendix H.

For this analysis, the rubric was used to assess the falling bodies and momentum and energy lab reports. The falling bodies lab report was chosen for analysis to provide a baseline for how students analyzed their results. In the two previous experiments (Measurement and
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Uncertainties, and Data Graphics and Analysis) students were instructed on the basics of data collection and introduced to several analysis techniques used by scientists. The momentum and energy lab reports (7th experiment) were used to evaluate how students’ communicated their conclusions of their experimental results while using sufficient evidence, such as relationships between variables, to support their claim. As part of the ISLE project, Eugenia Etkina (Etkina, 2008) states it takes 5-8 weeks for students to develop scientific abilities.

Only lab reports of students who had completed both reports were analyzed (n=41, representing 80% of those who completed the course). A paired samples two-tail t-test was conducted to compare each of the 7 categories regarding sources of uncertainty, claim of hypothesis being supported or refuted, and use of evidence to support this in the selected lab reports.

Table 4.5. Paired sample t-Test scores for Argumentation

<table>
<thead>
<tr>
<th>Scientific Ability</th>
<th>Experiment</th>
<th>Mean</th>
<th>Variance</th>
<th>t(df=40)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to identify sources of experimental uncertainty</td>
<td>Fb</td>
<td>1.27</td>
<td>0.50</td>
<td>-2.31</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td>Me</td>
<td>1.58</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to identify the shortcomings in an experimental design and suggest specific improvements</td>
<td>Fb</td>
<td>1.02</td>
<td>1.56</td>
<td>-3.95</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Me</td>
<td>1.56</td>
<td>0.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sufficient claim</td>
<td>Fb</td>
<td>1.56</td>
<td>0.30</td>
<td>-3.76</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Me</td>
<td>1.92</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accurate claim</td>
<td>Fb</td>
<td>1.73</td>
<td>0.30</td>
<td>-4.33</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Me</td>
<td>2.31</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Genuine evidence</td>
<td>Fb</td>
<td>1.36</td>
<td>0.63</td>
<td>-3.06</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>Me</td>
<td>1.73</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sufficient evidence</td>
<td>Fb</td>
<td>1.09</td>
<td>0.39</td>
<td>-3.76</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Me</td>
<td>1.51</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adequate rational</td>
<td>Fb</td>
<td>1.24</td>
<td>0.24</td>
<td>-5.09</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Me</td>
<td>1.78</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Although each of the seven categories showed statistically significant differences (p<0.025) between the two experiments, three of them showed particular improvement including “making an accurate claim”, “use of adequate rationale”, and “ability to identify shortcomings in experimental design and make suggestions for improvement”. These results suggest that students increased their understanding of how to make an accurate claim about their results which answers the research question and provide an explanation for how the evidence supports the claim. The third area in which students showed marked improvement was in their ability to correctly identify shortcomings in their experimental design and to suggest appropriate improvements to that design.

A reason why these specific results are prominent compared to the others may be that the momentum and energy experiment is the 7th experiment in a series of eight. The scientific processes targeted in the course were introduced to students in experiments one through six, so no new information other than the physics content associated with the experiment itself were included in this 7th lab session. In addition, by this time in the course students have had repeated practice applying the targeted science processes and have become more accustomed to writing lab reports and understanding what is expected.

Student Response to the Laboratory Experience

Two approaches were taken to address the second research question “How do students respond to the reformed lab experience?” That is, student views were sought via survey regarding their participation in the laboratory course, and student interactions with the laboratory activities were documented by the Teaching Assistants for each laboratory section via a guided interview by the researcher. Student opinions of the laboratory experience are important for several reasons. If students enjoy the experience, they are more engaged in the process. If
students determine the laboratory experience is worthwhile, they ask more thought provoking
questions to learn more about the concepts being tested by the experiments. This in turn, may
lead to better performance not only in the laboratory setting, but the lecture course as well.

This section presents data on students’ response to the SR-focused laboratory teaching
method (in both the initial and second study) as well as the traditional method (in the initial
study). There are two sections, Survey Data and TA Perspective. The first section has 5
subsections:

- Effect of lab experience on student views of learning
- Student views on feedback of physics knowledge
- Student preferences on performance in the laboratory
- Feedback from students on lab experience
- Student participation and interactions

**Survey data.**

Students were asked their opinions on their laboratory experience through a 20 question
anonymous survey which contained eight Likert scale questions and seven open-ended questions
(see Appendix I for the survey). The survey was administered to better understand students’
learning preferences after taking the course as well as how they perceived the laboratory
experience. Demographic information was also collected to determine if such things as previous
science experience or choice of major was relevant to the learning experience. This was
necessary given that the surveys were administered anonymously.
Effect of lab experience on student views of learning.

At the University of Cincinnati the physics lecture, laboratory course and recitation sessions are taught independently and although the same general topics are covered in each, they do not necessarily cover the same material at the same time. Table 4.6 presents student views as measured by two Likert scale questions on how the physics lab course has impacted their learning in the lecture course and recitation sessions. The data indicates that the traditionally taught laboratories are not viewed as strongly by students for preparing them for the lecture or recitation parts of the course. In terms of lecture, only 72% of the students in the traditional (alg-based) sections indicated the lab activities at least moderately helped in preparing them whereas in the SR-focused sections this was 100% (alg-based) and 80% (calc-based). This is an interesting finding and may be attributed to how the SR-focused laboratory activities are conducted when compared to the regular sections. That is, in the alternative lab activities the students are given more ownership of the learning and must develop their own experimental design which focuses heavily on the content covered in lecture. This better connection to the lecture material may have helped students view lab as a more integral part of the course learning.

As for recitation, 58% of the students in the traditional (alg-based) sections indicated the lab activities at least moderately helped in preparing them whereas in the SR-focused sections this was 80% (alg-based) and 70% (calc-based) of students. Note that in recitation the algebra-based sections completed typical end-of-chapter problems in a large lecture setting and the calculus-based sections completed conceptual worksheets from the *Tutorials in Introductory Physics*. These differences in recitation curriculum may account for the differences observed between the two groups. However, it is again interesting that the algebra-based physics students were more positive about the impact of the reformed lab activities in preparing them for
Reforming the intro physics lab to impact SR recitation, but given the nature of the algebra-based recitations which are conducted in a large lecture setting, this aligns with student responses on the former survey question about lab preparing them for the lecture part of the course. It is interesting that the calculus-based physics students found lab to be supportive of recitation, but this is understandable given that the SR-focused laboratory activities typically began with a discussion about the content to be addressed, which included visual representations and discussions of the calculations relevant to the experiment.

Table 4.6. Student views on how the physics lab course has impacted their learning

<table>
<thead>
<tr>
<th>Physics lab helped me:</th>
<th>understand lectures better</th>
<th>prepare for recitations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Algebra-Based SR-focused</td>
<td>Calculus-Based SR-focused</td>
</tr>
<tr>
<td>Score</td>
<td>1 – Helped</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>8.33%</td>
<td>49.41%</td>
</tr>
<tr>
<td></td>
<td>31.82%</td>
<td>59.09%</td>
</tr>
<tr>
<td></td>
<td>28.57%</td>
<td>26.53%</td>
</tr>
<tr>
<td></td>
<td>0.00%</td>
<td>17.86%</td>
</tr>
<tr>
<td></td>
<td>9.53%</td>
<td>33.33%</td>
</tr>
<tr>
<td></td>
<td>14.29%</td>
<td>24.49%</td>
</tr>
</tbody>
</table>

An open-ended question about what aspects of the lab activities students found useful in preparing them for the lecture course provides some insight into what was observed on the questions in Table 4.6. Table 4.7 provides the range of student responses to this question. As shown, the SR-focused sections lean towards a preference of physics concepts and their application to real life situations. When students observe experiments as real-life applications it
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solidifies their conceptual learning, which is then transferable to the lecture course as indicated by Table 4.6. One aspect of the SR-focused lab instructions was to discuss how experimental concepts translated into specific references to careers and every day life.

Students in both the traditional and SR-focused lab settings found the data analysis to be useful in preparing for lecture. The data analysis provides students with several different avenues to understand their experimental results. When more than one way of analysis is used to communicate and verify results, students find out new information about the physics involved. For example, if students only look at a list of data in chart form and do not graph the data, they may overlook the outlying data point which alters their results or the trend that is developing. These skills can transfer to lecture and recitation by providing skills necessary to approach physics problem sets in multiple ways to get the answer and to have a better understanding of the underlying physics.

Table 4.7 also shows 18.75% of students in the calculus-based SR-focused lab found the physics concepts as part of the experiments to be useful in the lecture course. Students expressed informally in their lab classes that it was beneficial to cover the same topics in both lecture and lab because this allowed them to solidify their knowledge. A subset of students, 14.58%, felt learning concepts in the laboratory first was beneficial in preparing for lecture. Students commented in the lab classes that being able to see the concepts applied through the experiments made it easier to understand these concepts when discussed in the lecture course.
Table 4.7. Aspects of lab cited by students as useful in preparing for lecture

<table>
<thead>
<tr>
<th>Frequent Comments</th>
<th>Algebra-Based Traditional</th>
<th>Algebra-Based SR-focused</th>
<th>Calculus-Based SR-focused</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application of concepts to real life / relate to lecture</td>
<td>19.05%</td>
<td>23.81%</td>
<td>31.25%</td>
</tr>
<tr>
<td>Data Analysis</td>
<td>19.05%</td>
<td>19.05%</td>
<td>14.58%</td>
</tr>
<tr>
<td>Background</td>
<td>4.76%</td>
<td>19.05%</td>
<td>0%</td>
</tr>
<tr>
<td>Lectures from TA</td>
<td>19.05%</td>
<td>19.05%</td>
<td>10.42%</td>
</tr>
<tr>
<td>Performing labs before learning concepts in lecture</td>
<td>4.76%</td>
<td>4.76%</td>
<td>14.58%</td>
</tr>
<tr>
<td>Hands on activities</td>
<td>14.29%</td>
<td>9.52%</td>
<td>16.67%</td>
</tr>
<tr>
<td>Physics concepts</td>
<td>0.00%</td>
<td>0.00%</td>
<td>18.75%</td>
</tr>
<tr>
<td>None</td>
<td>14.29%</td>
<td>4.76%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

**Student views on feedback of physics knowledge.**

In Table 4.8 students’ considerations regarding feedback on their physics knowledge is presented. Overall, both the traditional and SR-focused lab courses appeared to provide good feedback to students. The data indicates that when comparing all three categories, the SR-focused labs provided better feedback to students in terms of their learning. Regarding student understanding, 85% of the algebra-based SR-focused group and 80% of the calculus-based SR-focused group and 77% of traditional lab students claimed to receive adequate feedback. When evaluating if new physics was learned in lab that was not taught in the lecture course, 100% and 83% of the SR-focused lab courses (alg-based and calc-based, respectively) and 85% of traditional students agreed. Students in the lab classes indicated that answering the questions included in the experiment manuals gave students additional information that was not always covered in the lecture. Additionally, by performing the various types of data analysis, such as producing line graphs or histograms and comparing this with calculations, students stated they were able to better understand variable relationships, trends in the data and comparisons of data.
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The data seen in the last portion of Table 4.8 is supportive of the data shown to this point. Students strongly indicate (100% alg-based, 88% calc-based) that the SR-focused lab courses made them think more deeply about the physics concepts; this is more so than the traditional lab course (76%). This is likely due to the design of the SR-focused lab curriculum which encouraged students to think independently about the scientific processes involved in each experiment through guided lab questions. For comparison, the traditional lab setting provides a detailed, step-by-step set of instructions, which does not promote students to think beyond what is given to them for each experiment.

Table 4.8. Students’ considerations regarding feedback on their physics knowledge

<table>
<thead>
<tr>
<th>Physics lab gave me feedback on what I knew and didn’t know</th>
<th>I learned new physics concepts in physics lab</th>
<th>Physics lab helped me think more deeply about course materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>Alg Trad</td>
<td>Alg SR</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>1 Yes</td>
<td>0.00%</td>
<td>18.18%</td>
</tr>
<tr>
<td>2</td>
<td>63.69%</td>
<td>45.46%</td>
</tr>
<tr>
<td>Moderate</td>
<td>13.69%</td>
<td>31.82%</td>
</tr>
<tr>
<td>4</td>
<td>18.45%</td>
<td>4.55%</td>
</tr>
<tr>
<td>5 No</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

** The lecture instructor for the calculus-based SR-focused course made a point to connect lecture and lab topics during the lecture classes. Therefore, the lack of shift in learning new concepts in the laboratory is expected.

Student preferences on performance in the laboratory.

The following two tables indicate students desire a richer laboratory experiment. In particular, students in the SR-focused laboratories show a higher preference for thinking at a
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higher level and problem solving in the lab setting more so than those in the traditional labs classes. This data supports the reasoning presented in the last section of Table 4.3.

Table 4.9. Student preferences in the lab setting

Feedback from students on lab experience.
Students provided a variety of responses identifying what was useful in the laboratory setting and what could be improved. Table 4.10 shows an example of some of the more frequent responses. Students were asked to state what they considered the highlights of the lab experience as well as the low points. The following tables include 3 examples of the most frequent responses found within each treatment group along with the response rates of students in the other treatment groups for these same items.
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Table 4.10. Frequent responses of what was useful in lab and what could be improved

<table>
<thead>
<tr>
<th>What part of participation in lab would you consider the highlight</th>
<th>Frequent Comments</th>
<th>Consider the low point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Algebra-Based Traditional</td>
<td>Algebra-Based SR-focused</td>
</tr>
<tr>
<td>Working in Groups</td>
<td>0.00%</td>
<td>38.10%</td>
</tr>
<tr>
<td>All Experiments</td>
<td>23.81%</td>
<td>4.76%</td>
</tr>
<tr>
<td>Good TA interaction</td>
<td>19.05%</td>
<td>9.52%</td>
</tr>
<tr>
<td>Lab Instructions / Excel template</td>
<td>14.29%</td>
<td>0.00%</td>
</tr>
<tr>
<td>None</td>
<td>14.29%</td>
<td>4.76%</td>
</tr>
</tbody>
</table>

Of note in Table 4.10 is that students in the SR-focused sections preferred working in groups to accomplish their laboratory goals. Group work provides immediate feedback to students when critically thinking about their experiment designs, hypothesis testing and data analysis. Many students enjoyed performing the experiments, working with the equipment and learning more about the physics concepts being tested in a hands-on manner. This provides students with opportunities to observe how variables are related and how hypothesis-testing works in a real-life laboratory setting.

In addition to these comments, students in the calculus-based SR-focused sections also indicated highlights including: seeing the laws in action; making students figure out what to do for the lab; data sheets and data collection; reasoning tests; discussion of the formulas and why they were used; creating hypothesis, identifying variables and experimental design; good, well-organized lab write-up that was beneficial, feedback about the student experience. These
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comments are important as they were *explicitly* targeted areas of learning through the scaffolding process.

When students considered the low points of the laboratory experience, five categories stand out and are included in Table 4.11. Although lab students submitted lab reports that were six categories in length with the focused of the traditional reports being on data analysis, uncertainties and conclusions and the focus of the SR-focused reports on identification and relationships of variables, hypothesis testing and discussion of results, 10%-15% across all treatment groups cited the length and detail of the lab reports submitted for each experiment was difficult to complete. In the calculus-based SR-focused course, students were often confused about what to enter into their excel spreadsheet, as the course allowed for a ‘free form’ display of data and graphics. The calculations and analysis for each experiment were discussed as a whole class, but it was left to each group to decide how to present this information. The quizzes presented an issue for some of students in the algebra-based course as there are many options for students to choose from for each question. The use of Excel is difficult for students across the board. They are expected to learn how to use Excel from the start of the laboratory course, particularly in the algebra-based course (during initial study). This requirement was lightened in the calculus-based course (second study). And finally, there were a number of students who provided other feedback, such as: Not all sections of lab reports were graded (algebra/traditional), the initial instructions could be improved (all three courses), unprepared TAs, lab director not helpful (algebra/traditional), clearer instructions on lab report information (algebra/traditional), not having lab template for all experiments (algebra/traditional), Centorts (a multiple choice lab report; algebra/traditional), too many students(algebra/traditional), long tedious experiments / lack of variety, freedom (algebra/traditional).
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*Student participation and interactions.*

Another impact on student learning is their attendance and how they interact when in the lab. The survey results indicate that attendance across the three sections is very similar. Most students did not miss any lab classes (77% algebra/ SR-focused, 63% algebra/traditional, 77% calculus/ SR-focused). This is key to students’ learning, especially in the SR-focused lab setting. That is, if a student misses a lab, they don’t directly learn the scientific process piece taught that day, which they are then expected to include in future experiments and lab reports. Students have an opportunity to make-up missed labs within a week of the initially scheduled class. If the student must make up the lab at the end of the quarter, they are required to review the lab material for the missed lab so they do not fall behind on learning the new skills and abilities. In addition, students who do not perform an experiment lose the opportunity to understand the physics concepts involved or understand the relationships in the variables identified. In lab, students tended to ask clarifying questions of the TA and their peers. Although students in the SR-focused labs reported that the majority of questions were answered by TAs asking students probing questions (90% and 100% of time), students in the traditional labs reported that the TAs gave students the answer nearly a quarter of the time.

**Table 4.11.** TA response to student questions

<table>
<thead>
<tr>
<th></th>
<th>Algebra-Based Traditional</th>
<th>Algebra-Based SR-focused</th>
<th>Calculus-Based SR-focused</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gave Answer</strong></td>
<td>23.21%</td>
<td>9.52%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Asked Questions</strong></td>
<td>72.02%</td>
<td>90.48%</td>
<td>100.00%</td>
</tr>
<tr>
<td><strong>Didn't Help</strong></td>
<td>4.76%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>
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Students were queried if they preferred step-by-step instructions in the laboratory to get a better sense of student expectations. The previous tables have indicated that students in the SR-focused labs prefer a more robust (where they are required to think independently and are given challenges in which they must solve problems) laboratory experience and have found it benefitted their learning. Table 4.12 indicates students in the traditionally taught experiments prefer step-by-step instructions, while those taught the SR-focused labs demonstrated a tendency toward moderately structured instructions. Several individuals who have taken both the traditional lab and SR-focused lab courses commented that being able to answer questions as they performed the experiment and develop their own design was more beneficial to their understanding than given step-by-step instructions and specific data to replicate. Other students in the SR-focused labs have indicated to the researcher that the discussions prior to performing the experiment, thorough discussions of the equations that could be used for data analysis, and allowing student groups to discuss the variables, hypothesis and data analysis, gave them feedback on misconceptions along with confidence in their own understanding of the concepts.

Table 4.12. Student preference for lab instruction

<table>
<thead>
<tr>
<th>Preference</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>high</td>
<td>100%</td>
</tr>
<tr>
<td>moderate</td>
<td>80%</td>
</tr>
<tr>
<td>low</td>
<td>60%</td>
</tr>
</tbody>
</table>

[Bar chart showing student preference for lab instruction across different courses and preference levels.]
Teaching Assistant Interviews.

The two TAs who taught during the initial study were interviewed at the end of the term to obtain their opinions of how students responded to the SR-focused method. Both are seasoned TAs and taught one traditional and one SR-focused lab for comparison. The interviews were performed independently, however, both responded similarly to each of the open-ended questions. Their responses indicate that the SR-method was an acceptable teaching method and found no difficulties in using the scaffolding or prompts provided. The use of scaffolding to teach new information coupled with the lab reports focusing on scientific reasoning skills led them to believe their students improved reasoning and problem solving skills as demonstrated by their lab reports. Regarding time required for TA responsibilities, the two TAs indicated they used no additional preparation time for the SR-focused labs than for the traditional labs. The time spent grading student lab reports each week for the SR-focused labs was slightly increased over the time to grade traditional lab reports. This is to be expected as the SR-focused lab reports require students to include more text in the reports than the traditional lab.

The TAs both recommended that students work in groups of 3; or if students work in groups of 4, then a specific plan should be designed to ensure all students share responsibilities for the experimental procedures. And lastly, providing a formal TA manual for teaching the SR-focused labs was recommended for new TAs who had no previous laboratory teaching experience.
Chapter 5

Discussion

The results of this study support that reported in the research literature in that SR-focused curriculum better promotes student development of certain reasoning abilities. In particular, within the SR-focused lab courses significant improvements were observed in the areas of student ability to identify and control variables as shown by both Lawson scores and lab report rubric analysis, and ability to engage in argumentation as shown by the lab report rubric analysis. These were expected because identification and control of variables, identification of uncertainties, using evidence to support conclusions and determination of improvements to experimental design were specifically targeted in the SR-focused labs. In addition, students were provided ample opportunities to practice identification of variables when designing their experiments, along with practice in determining how uncertainties, assumptions and constraints affect results and using evidence-based reasoning to make their claim when writing the lab reports. As students progressed from simple pendulum experiments to more complex experiments such as centripetal forces or momentum and energy, the concept of control of variables and how to include sufficient evidence to provide adequate rationale about their conclusions became more obvious to the students and subsequently became an integral part of their work in lab.

Although it was expected that students would make significant gains in the area of hypothetical-deductive reasoning, this was not observed in the Lawson scores. This could be due to the Lawson questions in this domain being written about context unfamiliar or confusing to the students. On the other hand, significant gains were observed in the analysis of student lab
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reports within this domain. Improvements in the ability to adequately distinguish between a hypothesis and a prediction; identify assumptions associated with the experiments; and, determine how assumptions may affect their prediction show that students did make progress within some elements of this domain.

As further support for the impact of the SR-focused curriculum on student development of specific SR abilities, a comparison was made using student Lawson scores in the traditional lab course. For the students in the traditional course, significant shifts in the Lawson scores were not observed for any of the six ability domains.

Some limitations that may have impacted the magnitude of the findings include embedding the SR-focus method into the existing traditional experiments. This posed a challenge when writing the experiment instructions for the students and the TAs. Although the questions regarding the physics involved in each experiment were easily woven into the new SR-focused method, questions about study design and hypothesis testing were not always appropriate. Similarly in the initial study the same equipment was used in both the traditional and SR-focused labs. Since students were asked to determine their hypothesis to test and design their own experimental procedures, most groups came up with the same hypothesis. This did not provide for rich discussions at the end of the lab class as all groups were led to conduct the same experiment the same way. For the second study, we were able to obtain some additional equipment for students to use. However, this additional equipment was still limited and only provided students with one or two more options to write and test their hypothesis.

There may have also been limitations in having three TAs teach the six lab sections in the initial study. Since each TA taught one traditional lab and one SR-focused lab, there was no direct way to prevent one of the TAs from teaching some of the SR-focused methods in the
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traditional class or providing detailed instructions from the traditional class to the SR-focused class. Attempts were made to prevent this as the researcher met with the TAs weekly and discussed how they taught the previous classes and reiterated that the structure of the lab classes should be taught as designed. If any issues arouse from teaching the two different labs, solutions were discussed and then were rectified.

The laboratory students were given the Lawson test in person as a paper and pencil test. However, the lecture students took the test online. We have found nothing from the research literature to indicate students test differently whether through pencil and paper or online.

Although the true limitations of this discrepancy are not known, students in the lecture may have performed better on the test as they would have outside resources, such as information from the internet, available to them to answer the questions or they may have felt less pressure to perform given they completed the test at their convenience.

Another limitation may be from the research methodology. This research presents no inter-rater reliability, as the researcher (graduate student) was the only scorer of the lab rubric analysis. Ideally, a second or third scorer would have been employed to remedy this limitation. By only having a single scorer presents a bias which may positively or negatively skewed the results, for example, by reflecting student performance in the laboratory rather than actual performance on the particular skills emphasized. Additionally, if the scorer misinterpreted one section of the rubric and had not feedback from other scorers, this could artificially inflate the scores in that domain which could result in a falsely identified significant gain.

Also through this study we have evidence that students react favorably to this type of instruction. In particular, through surveys students in the SR-focused lab course indicated some of the benefits were in the areas of learning new physics, preparing them for the lecture and
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recitations parts of the course (particularly application of concepts in real life situations, the physics concepts in lab and data analysis), thinking more deeply about the course materials and working in groups. These were expected because students engaged in whole class and group discussions throughout the lab class using guiding questions which specifically related to the physics involved in each experiment and how the concepts may be applied to every day life or specific careers. In addition, each group was prompted to discuss their results to ensure the data they collected made sense and was appropriate for the type of experiment they were performing.

Positive student responses indicate that the SR-focused curriculum, where students extend their thinking through group discussions and engage in group problem solving as they determine the best design to test their hypothesis, is preferred by the majority of students. It is interesting to note that the traditional lab students show a moderately high preference for labs that extend thinking and require problem solving, yet they highly prefer labs with step-by-step instructions. This could be due to the fact that these students have not been exposed to any other type of learning style in a laboratory setting and find the step-by-step instructions comfortable.

Some limitations that may have impacted the findings regarding student lab preferences may involve different interpretations of the teaching instructions during the initial study, as identified in the weekly TA meetings. For example, one TA interpreted the discussion of experimental designs to mean that the entire class would determine which group designed the best set of procedures for the entire class to use, while another TA interpreted this as each group would share their experimental design with the class, and each group would then move forward with their own set of procedures. Attempts were made to minimize these differences, however, through weekly planning meetings between the researcher and the TAs.
In the second study only the researcher taught the three lab sections and as a result researcher bias may have been introduced in the teaching as well as the grading. This may have impacted students’ positive reactions to the SR-focused labs. In addition, all three sections did not receive identical treatment. For instance, the researcher noted that the instructions to the first lab class taught each week were not as complete as was initially though and adjustment were made by the third lab section each week. This is to be expected, as researcher/instructor became more accustomed to teaching the material and was able to improve the organization of the presentation and discussion with the students. Attempts were not made to keep all three sections the same as it was felt important that the curriculum be improved whenever possible.

Additionally, the population in the second study included a very diverse group of students. Some students were taking physics lab for the first time, some students were retaking the lecture and/or the introductory lab course and some students were enrolled in the second physics course in the introductory sequence while also taking this first lab class in the course. It isn’t entirely certain how these differences may have impacted the results of this study as parsing out the groups created sample sizes that were too small for statistical analysis. However, it was observed that students who previously took the physics lab class were already familiar with some or all of the experiments and already knew what data to collect and how to analyze it. This initially limited the amount of group discussion these groups engaged in when designing their group experiment as the student(s) who previously took the course informed the other group members of what needed to be done. When the TA queried the groups on their design, the students were redirected to follow the instructions for the SR-focused course and not the traditional lab. Additionally this same population did not initially follow directions regarding what was to be included in the group’s Experimental Information Sheets or the organization of
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the data placed in Excel. These students initially did not include the list of variables, hypothesis or experimental design on their Information Sheet, as instructed to do so for the SR-focused labs. Some groups automatically opened the traditional lab’s Excel spreadsheet template (all the computers in the laboratory area contained documents related to the traditional lab) and tried to use it rather than develop their own plans for data analysis. Again, students were redirected to the instructions for the SR-focused labs. The TA discussed with students any concerns or misunderstandings they had about what was required in the laboratory. In addition, the students who previously took the first quarter of the physics lecture course may have had a greater baseline of physics knowledge which may have given these students an advantage in being able to assess their data and provide appropriate argumentation in their lab reports.

The two studies as part of this research project could be viewed as a pilot for future studies to improve the laboratory experience. Future studies might include further modifications to the experiments that students perform as part of the introductory physics course. This may include choosing different lab experiments that better lend themselves to student engagement in the full scientific process, providing more targeted instruction earlier in the course to ensure students have more opportunity to practice and apply their abilities particularly those that did not incur significant gains in these initial studies, and providing more explicit guidance in the writing of lab reports. In particular, more attention on student sharing of data within the lab itself as a means of working together as a scientific research community, much like that done in modeling instruction (such as Brewe, 2009), would be of benefit to the students in terms of their ability to engage in sense-making and evidence-based reasoning.

One challenge that will ultimately need to be addressed is how SR-focused labs can be scaled to a large number of sections. The two studies included in this research involved only 3-6
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lab sections and up to three TAs. In order for the SR-focused method to be more widely adopted across a larger number of lab sections, issues involved in TA training and lab report grading must be resolved. The current SR-focused student lab instructions do not include high levels of detail of what the whole class should be doing at a given time. For example, TAs lead whole class discussions periodically throughout each lab class and these are conducted based on where the TA observes the class to be at any given time. More directed student lab sheets with built in “checkpoints” for class discussions could improve TA ability to conduct these labs but more work is needed in this area. Student lab manuals and TA training guides may help address this concern. Under the current SR-focused method, TAs grade a large number of lab reports each week using a detailed lab rubric. Streamlining this process is essential. It is possible that students could engage in longer lab investigations that span multiple weeks and therefore only submit lab reports every 3 weeks. Different parts of the lab reports could be emphasized each week with students submitting only the related parts each week. And it is possible that the lab reports could be integrated into the current lab report submission system currently in place for the traditional labs to help manage the large number of reports. More work is certainly needed and guidance from the lab instructors in the introductory biology course may be sought. A lesser issue involves the cost of additional equipment but that is believed to be minimal.
Bibliography


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APPENDICES

Appendix A

List of Experiments Performed for the Initial and Second Studies, All Sections

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## Appendix B

### Approach to Science Methods, Traditional and SR-Focused

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<th>Experiment</th>
<th>Scientific Processes Taught in Traditional Labs</th>
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| Measurement and Uncertainties | • Uncertainty of measured quantity  
  • Propagation of uncertainty  
  • Random, systematic uncertainties  
  • Standard deviation, standard error  
  • Histogram, normal distribution  
  • Repeatability  
  • Accuracy, precision  
  • Scale limited error  
  • Standard Equivalency Test (compares experimental and given values)  
  • Excel | • Research, collaboration, measuring, concept of uncertainty, observation  
  • Experimental design  
  • Research question  
  • Introduction of variables  
  • Assumptions and constraints  
  • Basic data analysis |
| Data Graphics                | • Least squares fit / LINEST  
  • Formatting and special characters in Excel  
  • Graphing – labels, fit line, error bars | • Research question  
  • Variables – IV, DV, CV  
  • Data analysis – calculations and graphing  
  • Least Squares Fit, trendline |
| Falling Bodies              |                                                                                                                   | • Prediction  
  • Replication  
  • Comparisons  
  • Standard Equivalency Test |
| Vector Forces               | • Polar and Cartesian Coordinates  
  • Vector Components  
  • Vector Addition | • Prediction  
  • Replication  
  • Comparisons  
  • Standard Equivalency Test |
| Newton’s Laws                |                                                                                                                   | • Writing a formal hypothesis  
  • Random, systematic, measured, propagated uncertainties |
| Centrifugal Forces           |                                                                                                                   | • Writing a formal hypothesis  
  • Random, systematic, measured, propagated uncertainties |
| Momentum and Energy          | Ratios of Momentum and ratios of energy |                                                                                                                   |
| Angular Acceleration         |                                                                                                                   |                                                                                                                   |
Appendix C

SR-Focused Experiment Instructions Provided to Students (initial study)

Student Version SR-Focused – Winter 2012

Experiment 1: Measurement and Uncertainty

Pre-lab

Please do the following BEFORE coming to your lab class:
- Read the background information provided on blackboard
- Take the quiz related to this lab
- Print off a copy of the laboratory write-up or use a specific notebook to keep track of your information for the labs

Learning Objectives:

Students should be able to:
- Create an experimental design
- State measurement and units for length, mass and time.
- Recognize no measurement is exact
- Determine what may cause an uncertainty in a measurement
- Understand the general relationships among position, velocity, and acceleration for the motion of a particle.
- Understand the special case of motion with constant acceleration, so they can:
  - Write down expressions for velocity and positions as functions of time
  - Use appropriate equations for velocity and displacement to solve problems involving one-dimensional motion with constant acceleration.

Equipment:
- Pendulum
- Stopwatch
- Computer

Experiment Information Sheet should contain:
- Experimental question(s) to be answered
- Design / Procedures
- Observations
- What data depends on other data (list both)

The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why you will be comparing and discussing your designs and results.

Whole Class:
1. In this class you will learn about:
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a. **Research**: A systematic investigation, which provides knowledge for new ideas, solves problems, or develops new theories

b. **Collaboration**: To work together with other researchers (students) in an intellectual endeavor toward a common goal

c. **Making Measurement**: The act of determining the dimensions, capacity or amount of something

d. **Concept of uncertainty**: A parameter associated with the doubt about the validity of the result of a measurement, which can be attributed to the instruments, design or researcher.

e. **Observation**: Anything you see, hear, smell, taste, or touch is an observation. Scientists obtain a great deal of the evidence they use by observing natural and experimentally generated objects and effects.

2. What questions are we trying to answer given the equipment and background?

3. How can we evaluate length of the pendulum without measuring it?

4. What method should be used to test the period of a pendulum given the equipment?
   a. What do we need to measure?
   b. What is given to us / can we consider any known values?

5. Now it is time to figure out how to test your method, called an experimental design.
   a. Creating an experimental design requires discussion between researchers (you, the students are considered researchers in this class). You should consider different ideas for your testing method. We will discuss this more as the quarter progresses.

   b. In this lab, we’ll give you some help at creating the design. Each group will take a turn at using the pendulum. Each group will measure 1 single swing then multiple swings (either 3, 5 or 10 swings).
      i. Discuss why you might want to use this design?
      ii. How will it answer your questions (that you came up with in #2 above)?
      iii. Make sure that you write this information down on this form or in a notebook— your design, how you came up with it, why you want to use it, how it will answer your questions. You will need this information when writing your lab report.

6. What type of data is to be collected?
   a. Length of pendulum, time of swings
   b. Create a chart in Excel for these values

7. Perform experiment, collect data
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a. Each group will measure 1 single swing at a small angle - about 10 degrees

b. Each group will then take time measurements for a different number of swings (each group chooses one of the following):
   i. 3 swings (do this two times)
   ii. 5 swings (do this once)
   iii. 10 swings (do this once)

8. Given the design
   a. An assumption is something taken for granted or accepted as true without proof.
      i. What assumptions can we make?

   b. A constraint is anything that limits the experiment. It can be internal or external and sources may include equipment, researchers or outside factors.
      i. What constraints should we consider?

**Discuss as whole class – how to get an uncertainty value from the design.**

Where can errors occur in measurements, data collection?

9. How might you analyze the data?
   a. Are there any calculations or graphs you might want to use?
   b. What do the data indicate initially – does it look correct?
   c. What are you comparing?
      i. What data depends on other data (independent and dependent variables)?
   d. What observations did you make?

Groups:
10. Do calculations, histogram in Excel
11. Submit through In Class Analysis

Whole Class:
12. Did all of your initial questions get answered?
   a. If no, why not?

13. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

14. How could this experiment be used in the real world?

**Questions to be answered as part of your lab report:**
1. Three different techniques are used to measure the diameter and circumference of a circular object in order to find pi experimentally. Method A resulted in 3.133 ± 0.007, Method B gave 3.1609 ± 0.0002, and the result of Method C was 3.14 ± 0.03. Which of these methods were the most accurate and which was the most precise? Why?

2. If you wanted to build a pendulum that took a long time to make a full swing, what would you have to do about the length?

Turn in your Experimental Information Sheet to your TA before you leave class.

Submitting your In-Class Analysis through Blackboard opens a portal for you to be able to submit your Lab Report. You are required to submit your lab report through Blackboard in order for it to be graded. It will be checked by a software program called WebAssign to check for cheating.

Submit your lab report within 6 days of the beginning of your lab (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).

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**Student Version SR-Focused – Winter 2012**

**Experiment 2: Data Graphics and Analysis**

**Pre-lab**

Please do the following BEFORE coming to your lab class:

- Read the background information provided on blackboard
- Take the quiz related to this lab
- Print off a copy of the laboratory write-up or use a specific notebook to keep track of your information for the labs

**Learning Objectives:**

**Students should be able to:**

- State measurement and units for length, mass and time.
- Determine the difference between independent and dependent variables; what variables are held constant as controls
- Understand the general relationships among position, velocity, and acceleration for the motion of a particle.
- Understand how to use graphical representations in data analysis
- Understand the special case of motion with constant acceleration, so they can:
  - Write down expressions for velocity and positions as functions of time, and identify or sketch graphs of these quantities.
  - Use appropriate equations for velocity and displacement to solve problems
involving one-dimensional motion with constant acceleration.

**Equipment:**
- Tape measure
- Adjustable length pendulum with stand
- Photogate
- Computer with Science Workshop interface

**Experiment Information Sheet should contain:**
- Experimental question(s) to be answered
- Design / Procedures
- Observations
- What data depends on other data (list both)

The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

**Whole Class:**
1. In this class you will learn about:
   a. **Research:** A systematic investigation, which provides knowledge for new ideas, solves problems, or develops new theories
   b. **Collaboration:** To work together with other researchers (students) in an intellectual endeavor toward a common goal
   c. **Making Measurement:** The act of determining the dimensions, capacity or amount of something
   d. **Concept of uncertainty:** A parameter associated with the doubt about the validity of the result of a measurement, which can be attributed to the instruments, design or researcher.
   e. **Observation:** Anything you see, hear, smell, taste, or touch is an observation. Scientists obtain a great deal of the evidence they use by observing natural and experimentally generated objects and effects.

2. What questions are we trying to answer?

3. How can we evaluate the relationship between the period of a pendulum and the length of a pendulum?

4. Why are these questions important?

**Groups:**
5. What method should be used to test the period of the pendulum given the equipment?
   a. What do we need to measure?
b. What is given to us / can we consider any known values?

6. Now it is time to figure out how to test your method, called an experimental design.
   a. Creating an experimental design requires discussion between researchers (you, the
      students are considered researchers in this class). You should consider different
      ideas for your testing method. We will discuss this more as the quarter
      progresses.

b. In this lab we will learn how to identify independent and dependent variables
   i. **Independent variables**: In any experimental design, a researcher will
      manipulate one type of data called the independent variable, and will study
      how it affects other types of data collected.
         1. What is the independent variable in this experiment?

   ii. **Dependent variables**: The other types of data (from above) affected by
      the independent variable are called dependent variables.
         1. What is the dependent variable(s) in this experiment?

c. How can we **control variables**? A control variable is a variable that must not be
   changed throughout an experiment because it affects the dependent variables and
   thus affects the outcome of the experiment.
   i. What variables should we control in this experiment?

d. Last time we tested the times of various swings to find the length of the
   pendulum. How can we test the linear relationship of the variables?

e. Discuss why you might want to use this design?

f. How will it answer your questions?

g. Make sure that you write this information down on this form or in a notebook–
   your design, how you came up with it, why you want to use it, how it will answer
   your questions. You will need this information when writing your lab report.

**Compare Designs between groups**
**Discuss as whole class - Decide which is best or if more than one is ok.**

**Groups:**

7. What type of data is to be collected?
   a. Create chart in Excel

8. Perform experiment, collect data
   a. Are there variations in the measurements, method or data collection?
9. Given the design
   a. An assumption is something taken for granted or accepted as true without proof.
      i. What assumptions can we make?

   b. A constraint is anything that limits the experiment. It can be internal or external
      and sources may include equipment, researchers or outside factors.
      i. What constraints should we consider?

Whole Class:
10. How might you analyze the data?
   a. Are there any calculations or graphs you might want to use?
      i. In this lab you will learn how to perform a least squares fit: A
         mathematical procedure for finding the best-fitting line or curve to a given
         set of points by minimizing the sum of the squares of the errors made in
         solving each individual equation. Outlying points can have an effect on
         the fit, which may skew the fit line or curve. We call a linear fit a
         trendline.

   b. What do the data indicate initially – does it look correct?

   c. What are you comparing?
      i. What data depends on other data (independent and dependent variables)?

   d. What observations did you make?

Groups:
11. Do calculations and graphs in Excel
12. Submit through In Class Analysis

Whole Class:
13. Did all of your initial questions get answered?
   a. If no, why not?

14. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

15. How could this experiment be used in real life?

Questions to be answered as part of your lab report:
1. Two students doing this experiment came up with a slope for 1 vs. \((T/2\pi)^2\) of 9.86
   ± 0.04 m/s². How does this compare with the value it should be? (Are the two values
   equivalent?) Why?

2. A simple pendulum is known to have a period of oscillation \(T=1.55\) s. Amy uses a digital
   stopwatch to measure the total time for 5 oscillations and calculate an average period of \(T\)
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T = 1.25 s. Bob uses an analog wristwatch and the same procedure to calculate an average period for the 5 oscillations and finds T = 1.6 s. Which student made the more accurate measurement? Explain.

Turn in your Experimental Information Sheet to your TA before you leave class.

Submitting your In-Class Analysis through Blackboard opens a portal for you to be able to submit your Lab Report. You are required to submit your lab report through Blackboard in order for it to be graded. It will be checked by a software program called WebAssign to check for cheating.

Submit your lab report within 6 days of the beginning of your lab (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).

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Experiment 3: Falling Bodies

Pre-lab
Please do the following BEFORE coming to your lab class:
- Read the background information provided on blackboard
- Take the quiz related to this lab
- Print off a copy of the laboratory write-up or use a specific notebook to keep track of your information for the labs

Learning Objectives:
Students should be able to:
- Verify the rate of acceleration of a freely falling body, g
- Determine the relationship between velocity and time in free fall
- Determine the relationship between distance and time
- Understand the effect of drag forces on the motion of an object, so they can:
  - Describe qualitatively the acceleration, velocity and displacement of such a particle when it is released from rest.
  - Derive an expression for the acceleration as a function of time for an object falling under the influence of drag forces
  - Use Newton’s Second Law to write an equation for the velocity of an object as a function of time
- Understand how to make a prediction about an experiment
- Understand why replication of experiments is important

Equipment:
- Meter stick and 2-meter stick
- Ball bearing
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- Launcher for ball bearing
- Landing pad
- Science Workshop interface
- Computer

**Experiment Information Sheet should contain:**
- Experimental question(s) to be answered
- Design / Procedures
- Observations
- What data depends on other data (list both)

The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

**Whole Class:**
1. What questions are we trying to answer?
2. How can we evaluate velocity, acceleration for a falling body?
3. Why are these questions important?

**Groups:**
4. What method(s) should be used to test free fall given the equipment?
   a. What do we need to measure?
   b. What is given to us / can we consider any known values?

5. Now it is time to figure out how to test your method, called an experimental design.
   a. In this lab we will learn how to predict outcomes of the experiment and discuss why being able to replicate an experiment is important.
      i. **Prediction:** Your prediction lets you specifically state how you think your research questions will be answered. The experiment that you will design is done to test the prediction. Once you develop a prediction, you shouldn't change it, even if the results of your experiment show that you were wrong. An incorrect prediction does not mean that you "failed." It just means that the experiment brought some new facts to light that maybe you hadn't thought about before.
      ii. **Replication:** Confidence is added to results if an experiment is replicated by other researchers. This helps confirm that the previous results weren't dependent on some unreported aspect of the first experiment and that it wasn't the result of a statistical fluke or sloppy or fraudulent work. We are
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doing replication style experiments in this lab class.

b. What are the independent and dependent variables?

c. What variables should we control in this experiment?

d. Discuss why you might want to use this design?

e. How will it answer your questions?

f. Is this a design that could easily be replicated by other scientists?

g. Using this design, what do you predict will happen; what values will we obtain?

Compare Designs between groups
Discuss as whole class - Decide which is best or if more than one is ok.

Groups:
6. What type of data is to be collected?
   a. Create chart in Excel

7. Perform experiment, collect data
   a. Are there variations in the measurements, method or data collection?

8. Given the design
   a. What assumptions can we make?
   b. What constraints should we consider?

Whole Class:
9. How might you analyze the data?
   a. We discussed independent and dependent variables earlier. How do you plot these on a graph?
      i. Which axis do you place the dependent variable? The independent variable?
   b. What do the data indicate initially – does it look correct?
   c. What are you comparing?
      i. What data depends on other data (independent and dependent variables)?
   d. What observations did you make?

Groups:
10. Do calculations and graphs in Excel

11. In this lab you will do a more formal Excel sheet.
   a. Please include the experiment name, today’s date, the names of students in your
group near the top of the excel page.
   b. When doing your calculations, graphs, and compared data, make sure these
sections are organized and the data flows in a logical manner (such as placing the
measured/collected data first, calculations, and then the graphs).

12. Submit Excel page through In Class Analysis

Whole Class:
13. Did all of your initial questions get answered?
   a. If no, why not?

14. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

15. How could this experiment be used in real life?

Questions to be answered as part of your lab report:
1. A student decides to test the average acceleration of his iPod falling from the window of
a room on the 3rd floor of Braunstein Hall. He uses a meter stick to measure the height
and the stopwatch on his wristwatch to collect data. He finds for the 3 trials: heights =
5.25 m, 5.18 m, 5.23 m, times = 1.14 s, 1.19 s, 1.15 s. What is the average acceleration?

2. Is the diver below correct in his calculation? If he steps off that board, how fast in miles
per hour would he be going when he hits the water? Show your work.

Is this guy really a whiz?
Turn in your Experimental Information Sheet to your TA before you leave class.

Submitting your In-Class Analysis through Blackboard opens a portal for you to be able to submit your Lab Report. You are required to submit your lab report through Blackboard in order for it to be graded. It will be checked by a software program called WebAssign to check for cheating.

Submit your lab report within 6 days of the beginning of your lab (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).

Student Version SR-Focused – Winter 2012
Experiment 4: Vector Forces

Pre-lab
Please do the following BEFORE coming to your lab class:
- Read the background information provided on blackboard
- Take the quiz related to this lab
- Print off a copy of the laboratory write-up or use a specific notebook to keep track of your information for the labs

Learning Objectives:
Students should be able to:
- State what a vector is and gain experience working with vectors
- Demonstrate the process of adding vectors
- Use two independent methods for demonstrating the relationship between vector addition and a resultant vector
- Identify the relation between the force that acts on an object and the resulting change in the object’s velocity, so they can:
  - Determine, for an object moving in a plane whose velocity vector undergoes a specified change over a specified time interval, the average force that acted on the object.
  - Understand how Newton’s Second Law $F = F_{net} = ma$, applies to an object subject to forces such as gravity, the pull of strings, or contact forces, so they can write down the vector equation that results from applying Newton’s Second Law to the object, and take components of this equation along appropriate axes.
- Determine how to make a prediction about an experiment
- Understand why replication of experiments is important

Equipment:
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- Colored pencils
- Drawing compass
- Protractor
- Drafting triangle
- Straightedge (ruler)
- Plain white paper
- Triple beam balance
- Force table with 4 pulleys
- Strings
- 4 Mass hangers
- Various slotted masses

**Experiment Information Sheet should contain:**
- Experimental question(s) to be answered
- Design / Procedures
- Observations
- What data depends on other data (list both)

The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

**Whole Class:**
1. This lab will have two experiments using vectors – a hand drawn graphical representation and an experiment with equipment where you collect data.

2. What questions are we trying to answer?

3. How can we evaluate vector forces in 2 dimensions?

4. Why are these questions important?

**Groups:**
5. What methods should be used to test vector laws of addition and vector forces given the equipment?
   a. What do we need to measure?
   
   b. What is given to us / can we consider any known values?

6. Now it is time to figure out how to test your method, called an experimental design.
   a. In this lab we will learn how to predict outcomes of the experiment and discuss
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why being able to replicate an experiment is important.

i. **Prediction:** Your prediction lets you specifically state how you think your research questions will be answered. The experiment that you will design is done to test the prediction. Once you develop a prediction, you shouldn't change it, even if the results of your experiment show that you were wrong. An incorrect prediction does not mean that you "failed." It just means that the experiment brought some new facts to light that maybe you hadn't thought about before.

ii. **Replication:** Confidence is added to results if an experiment is replicated by other researchers. This helps confirm that the previous results weren't dependent on some unreported aspect of the first experiment and that it wasn't the result of a statistical fluke or sloppy or fraudulent work. We are doing replication style experiments in this lab class.

b. What are the independent and dependent variables?

c. What variables should we control in this experiment?

d. Discuss why you might want to use this design?

e. How will it answer your questions?

f. Is this a design that could easily be replicated by other scientists?

g. Using this design, what do you predict will happen; what values will we obtain?

**Compare Designs between groups**

**Discuss as whole class - Decide which is best or if more than one is ok.**

**Groups:**

7. What type of data is to be collected?
   a. Create chart in Excel

8. Perform experiment, collect data
   a. Are there variations in the measurements, method or data collection?

9. Given the design
   a. What assumptions can we make?

   b. What constraints should we consider?

10. Show your experimental results on a hand drawn graph. This will verify what you have come up with in your experiment.
Whole Class:
11. How might you analyze the data?
   a. What do the data indicate initially – does it look correct?
   b. What are you comparing?
      i. What data depends on other data (independent and dependent variables)?
   c. What observations did you make?

Groups:
12. Do calculations and graphs in Excel
13. In this lab you will do a more formal Excel sheet.
   a. Please include the experiment name, today’s date, the names of students in your
      group near the top of the excel page.
   b. When doing your calculations, graphs, and compared data, make sure these
      sections are organized and the data flows in a logical manner (such as placing the
      measured/collected data first, calculations, and then the graphs).

14. Submit Excel page through In Class Analysis

Whole Class:
15. Did all of your initial questions get answered?
   a. If no, why not?

16. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

17. How could this experiment be used in real life?

Questions to be answered as part of your lab report:
1. If all the hangers have the same mass, is it possible to neglect their weights because their
   contributions “cancel out” when the vector forces representing the string tensions are
   added together? Explain

2. Throughout this experiment, we have used the units “grams” to express the magnitude of
   the forces acting, and yet we know grams measure mass and not force. How can we do
   this, i.e., how can we be sure that the laws of vector addition are being validly tested?

Turn in your Experimental Information Sheet to your TA before you leave class.

Submitting your In-Class Analysis through Blackboard opens a portal for you to be able to
submit your Lab Report. You are required to submit your lab report through Blackboard in order
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for it to be graded. It will be checked by a software program called WebAssign to check for cheating.

Submit your lab report within 6 days of the beginning of your lab (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).

Student Version SR-Focused – Winter 2012
Experiment 5: Newton’s Laws of Motion

Pre-lab
Please do the following BEFORE coming to your lab class:

- Read the background information provided on blackboard
- Take the quiz related to this lab
- Print off a copy of the laboratory write-up or use a specific notebook to keep track of your information for the labs

Learning Objectives:
Students should be able to:

- State Newton’s Laws of Motion
- Analyze situations in which a particle remains at rest, or moves with constant velocity:
  - Under the influence of gravity
  - Under the influence of several forces
- Understand the relation between the force that acts on an object and the resulting change in the object’s velocity, so they can:
  - Calculate, for an object moving in one dimension, the velocity change that results when a force acts over a specified time interval.
- Understand the significance of friction, so they can:
  - Write down the relationship between the normal and frictional forces on a surface
  - Analyze situations in which an object moves along an inclined plane or horizontal surface.
- Identify the relationship between force and acceleration
- Understand how to perform calculations of uncertainties
- Identify comparisons between results and theoretical or given values and analyze the comparisons

Equipment:

- Metric tape measure
- Digital calipers
- Triple beam balance
- Air track
- Various aluminum blocks
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- 2 cars (gliders) of unequal mass with flags (aluminum inserts on top)
- Piece of string with tied loops at both ends
- Fishing bob
- Photogate
- Computer with Science Workshop interface

**Experiment Information Sheet should contain:**
- Experimental question(s) to be answered
- Design / Procedures
- Observations
- What data depends on other data (list both)

The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

**Whole Class:**
1. What questions are we trying to answer?
2. How can we evaluate an object moving down an inclined plane?
   a. Under gravity?
   b. Under an accelerating force?
3. What do we know about tension?
   a. How does acceleration change when an object is subject to a tension force?
4. Why are these questions important?

**Groups:**
5. What method(s) should be used to test motion and acceleration down an inclined plane given the equipment?
   a. What do we need to measure?
   b. What is given to us / can we consider any known values?

6. Now it is time to figure out how to test your method, called an experimental design.
   a. We discussed previously how to make a prediction about your results. Now you will make a formal statement called a hypothesis.
      i. Hypothesis basically means "a possible solution to a problem, based on knowledge and research." The hypothesis is a simple (general) statement
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that defines what you think the outcome of your experiment will be.

b. What are the independent and dependent variables?

c. What variables should we control in this experiment?

d. Discuss why you might want to use this design?

e. How will it answer your questions?

f. Is this a design that could easily be replicated by other scientists?

g. Using this design, what is your hypothesis (a general statement), what do you predict (a more specific statement) will happen; how might it answer your questions?

**Compare Designs between groups**

**Discuss as whole class - Decide which is best or if more than one is ok.**

**Groups:**

7. What type of data is to be collected?
   a. Create chart in Excel

8. Perform experiment, collect data
   a. Are there variations in the measurements, method or data collection?

9. Given the design
   a. What assumptions can we make?

   b. What constraints should we consider?

**Whole Class:**

10. How might you analyze the data?
    a. We have discussed the concept of uncertainty in measurements. Now we need to learn the different types of uncertainties (sometimes called errors).

    i. **Random uncertainties** occur due to slightly different measuring conditions and to disparate observer interpretations.

    ii. **Measured uncertainties** are considered random uncertainties: A quantity associated with the doubt about the validity of the result of a measurement. This means that if you measure a weight of 34.7 grams with an uncertainty (or doubt) of 0.3 grams, then we are saying the measurement is probably in the range of 34.4 g to 35.0 g. Therefore we would show our result as $34.7 \pm 0.3$ g. We represent the uncertainty as
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\[ u\{m\} = 0.3 \text{ g} \] – where the ‘m’ is whatever value is being measured – so m would be mass here; you would use x for distance, t for time, etc.

iii. **Systematic errors**: These uncertainties are due to conditions which are not taken into account during the experiment. They are reproducible and you may be able to compensate for them, if you recognize their affects on your results.

1. These types of errors may also be due to assumptions or constraints that were made in the experiment
2. Usually when discussing systematic errors we state what condition is affecting the results and how it may affect the results.

iv. **Propagated uncertainties**: This is a process of determining an uncertainty through a calculation.

b. Now you are ready to begin calculating uncertainties associated with your experiment.
   i. When doing these calculations, make sure to show step by step how you get from the value to its uncertainty.
   
   ii. Calculate the uncertainty of the following
       1. Length of the flag
       2. Theoretical acceleration

c. What do the data indicate initially – does it look correct?

d. What are you comparing?
   i. What data depends on other data (independent and dependent variables)?
   
   ii. How can we use the uncertainties when comparing data?
       1. One way we can show a comparison between experimental results and a given value is to calculate it through the **Standard Equivalency Test (SET)**.
       2. SET is the mathematical test you use to compare two numbers that are supposed to be equal. If the inequality is true, values A and B (below) are equivalent:
       3. We show this by calculating: \( A - B \leq 2 \sqrt{u A^2 + u B^2} \), where A is the theoretical or give value and B is the experimental value. A and B by itself are the values, while the \( u\{A\} \) and \( u\{B\} \) are the uncertainties associated with the values.

e. What observations did you make?

Groups:

11. Do calculations, uncertainties, graphs, and SETs in Excel
12. In this lab you will do a more formal Excel sheet.
   a. Please include the experiment name, today’s date, the names of students in your group near the top of the excel page.
   b. When doing your calculations, graphs, and compared data, make sure these sections are organized and the data flows in a logical manner (such as placing the measured/collection data first, calculations, and then the graphs).

13. Submit through In Class Analysis

Whole Class:
14. Did all of your initial questions get answered?
   a. If no, why not?

15. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

16. How could this experiment be used in real life?

Questions to be answered as part of your lab report:
1. If the string used to connect the small weight to the car in Part 2 had appreciable mass, would the car still undergo uniform acceleration? Explain.
2. The experimental value of the acceleration depends differently on the mass of the car for the first force than it does for the second force. Explain how this difference comes about.

Turn in your Experimental Information Sheet to your TA before you leave class.

Submitting your In-Class Analysis through Blackboard opens a portal for you to be able to submit your Lab Report. You are required to submit your lab report through Blackboard in order for it to be graded. It will be checked by a software program called WebAssign to check for cheating.

Submit your lab report within 6 days of the beginning of your lab (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).

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Student Version SR-Focused – Winter 2012
Experiment 6: Centripetal Force

Pre-lab
Please do the following BEFORE coming to your lab class:
- Read the background information provided on blackboard
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- Take the quiz related to this lab
- Print off a copy of the laboratory write-up or use a specific notebook to keep track of your information for the labs

**Learning Objectives:**

**Students should be able to:**

- Identify how circular motion compares with linear motion
- Define centripetal force and its relation to tension, gravity and friction
- Determine how to make a hypothesis
- Determine how to control variables
- Understand how to perform calculations of uncertainties
- Identify comparisons between results and theoretical or given values and analyze the comparisons

**Equipment:**

- 3-beam balance
- Rotating platform with base, rotary motion sensor, and motor
- Mass hanger
- Leader power supply and banana leads
- Science Workshop interface
- Computer

**Experiment Information Sheet should contain:**

- Experimental question(s) to be answered
- Design / Procedures
- Observations
- What data depends on other data (list both)

The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

**Whole Class:**

1. What questions are we trying to answer?
   
   a. What else do you know about springs?
   
   b. What else do you know about moving objects?

2. How can we evaluate uniform circular motion?

3. Why are these questions important?
Groups:
4. What method should be used to test uniform circular motion given the equipment?
   a. What do we need to measure?
   b. What is given to us / can we consider any known values?

5. Now it is time to figure out how to test your method, called an experimental design.
   a. We discussed previously how to make a prediction about your results. Now you will make a formal statement called a hypothesis.

   i. Hypothesis basically means "a possible solution to a problem, based on knowledge and research." The hypothesis is a simple (general) statement that defines what you think the outcome of your experiment will be.

   b. What are the independent and dependent variables?
   c. What variables should we control in this experiment?
   d. Discuss why you might want to use this design?
   e. How will it answer your questions?
   f. Is this a design that could easily be replicated by other scientists?
   g. Using this design, what is your hypothesis (a general statement), what do you predict (a more specific statement) will happen; how might it answer your questions?

**Compare Designs between groups**

**Discuss as whole class - Decide which is best or if more than one is ok.**

Groups:
6. What type of data is to be collected?
   a. Create chart in Excel

7. Perform experiment, collect data
   a. Are there variations in the measurements, method or data collection?

8. Given the design
   a. What assumptions can we make?
   b. What constraints should we consider?
Whole Class:
9. How might you analyze the data?
   a. We have discussed the concept of uncertainty in measurements. Now we need to
      learn the different types of uncertainties (sometimes called errors).
      i. **Random uncertainties** occur due to slightly different measuring
         conditions and to disparate observer interpretations.
      ii. **Measured uncertainties** are considered random uncertainties: A quantity
          associated with the doubt about the validity of the result of a
          measurement. This means that if you measure a weight of 34.7 grams
          with an uncertainty (or doubt) of 0.3 grams, then we are saying the
          measurement is probably in the range of 34.4 g to 35.0 g. Therefore we
          would show our result as 34.7 ± 0.3 g. We represent the uncertainty as
          \( u\{m\} = 0.3 \text{ g} \) – where the ‘m’ is whatever value is being measured – so m
          would be mass here; you would use x for distance, t for time, etc.
      iii. **Systematic errors**: These uncertainties are due to conditions which are
           not taken into account during the experiment. They are reproducible and
           you may be able to compensate for them, if you recognize their affects on
           your results.
           1. These types of errors may also be due to assumptions or
              constraints that were made in the experiment
           2. Usually when discussing systematic errors we state what condition
              is affecting the results and how it may affect the results.
      iv. **Propagated uncertainties**: This is a process of determining an
          uncertainty through a calculation.
   b. Now you are ready to begin calculating uncertainties associated with your
      experiment.
      i. When doing these calculations, make sure to show step by step how you
         get from the value to its uncertainty.
      ii. Calculate the uncertainty of the following
          1. Angular velocity
          2. Angular velocity squared
          3. \( \frac{1}{mr} \)
   c. What do the data indicate initially – does it look correct?
   d. What are you comparing?
      i. What data depends on other data (independent and dependent variables)?
      ii. How can we use the uncertainties when comparing data?
1. One way we can show a comparison between experimental results and a given value is to calculate it through the **Standard Equivalency Test (SET)**.

2. SET is the mathematical test you use to compare two numbers that are supposed to be equal. If the inequality is true, values A and B (below) are equivalent:

3. We show this by calculating: \( A - B \leq 2 \sqrt{u_A^2 + u_B^2} \), where A is the theoretical or given value and B is the experimental value. A and B by itself are the values, while the \( u_A \) and \( u_B \) are the uncertainties associated with the values.

e. What observations did you make?

Groups:

10. Do calculations, uncertainties, graphs, and SETS in Excel

11. In this lab you will do a more formal Excel sheet.
   a. Please include the experiment name, today’s date, the names of students in your group near the top of the excel page.
   b. When doing your calculations, graphs, and compared data, make sure these sections are organized and the data flows in a logical manner (such as placing the measured/collected data first, calculations, and then the graphs).

12. Submit through In Class Analysis

Whole Class:

13. Did all of your initial questions get answered?
   a. If no, why not?

14. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

15. How could this experiment be used in real life?

**Questions to be answered as part of your lab report:**

1. Why is it crucial that the string from the mass to the pulley is purely horizontal and that the support string hangs straight up and down?

2. When the radius is increased, does the period of the circular motion increase or decrease? Explain.

Turn in your Experimental Information Sheet to your TA before you leave class.

Submitting your In-Class Analysis through Blackboard opens a portal for you to be able to
submit your Lab Report. You are required to submit your lab report through Blackboard in order for it to be graded. It will be checked by a software program called WebAssign to check for cheating.

Submit your lab report within 6 days of the beginning of your lab (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).

Student Version SR-Focused – Winter 2012
Experiment 7: Momentum and Energy in 1D Collisions

Pre-lab
Please do the following BEFORE coming to your lab class:
- Read the background information provided on blackboard
- Take the quiz related to this lab
- Print off a copy of the laboratory write-up or use a specific notebook to keep track of your information for the labs

Learning Objectives:
Students should be able to:
- Define Conservation Laws
- Distinguish between elastic and inelastic collisions
- Understand linear momentum, so they can:
  - Explain how linear momentum conservation follows as a consequence of Newton’s Third Law for an isolated system
  - Identify situations in which linear momentum, or a component of the linear momentum vector, is conserved.
  - Apply linear momentum conservation to one-dimensional elastic and inelastic collisions
- Understand the concept of mechanical energy and of total energy, so they can:
  - State and apply the relation between the work performed on an object by non-conservative forces and the change in an object’s mechanical energy
  - Describe and identify situations in which mechanical energy is converted to other forms of energy
  - Analyze situations in which an object’s mechanical energy is changed by friction or by a specified externally applied force
- Understand conservation of energy, so they can:
  - Identify situations in which mechanical energy is or is not conserved
  - Apply conservation of energy in analyzing the motion of systems of connected objects
  - Apply conservation of energy in analyzing the motion of objects that move under the influence of other non-constant one-dimensional forces.
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- Recognize and solve problems that call for application both of conservation of energy and Newton’s Laws

**Equipment:**
- Digital calipers
- Triple beam balance
- Air track
- 2 differently sized air track cars (gliders)
- 2 photogates

**Experiment Information Sheet should contain:**
- Experimental question(s) to be answered
- Design / Procedures
- Observations
- What data depends on other data (list both)

The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

**Whole Class:**
1. What questions are we trying to answer?
   a. What do you know about momentum?
   b. What do you know about mechanical and kinetic energies?
   c. What do you know about collisions in 1 dimension?
2. How can we evaluate elastic collisions?
3. How can we evaluate inelastic collisions?

**Groups:**
4. What method should be used to test collisions in one dimension given the equipment?
   a. What do we need to measure?
   b. What is given to us / can we consider any known values?
5. Now it is time to figure out how to test your method, called an experimental design.
   a. What are the independent and dependent variables?
   b. What variables should we control in this experiment?
c. Discuss why you might want to use this design?

d. How will it answer your questions?

e. Is this a design that could easily be replicated by other scientists?

f. Using this design, what is your hypothesis (a general statement), what do you predict (a more specific statement) will happen; how might it answer your questions?

**Compare Designs between groups**

**Discuss as whole class - Decide which is best or if more than one is ok.**

**Groups:**

6. What type of data is to be collected?
   a. Create chart in Excel

7. Perform experiment, collect data
   a. Are there variations in the measurements, method or data collection?

8. Given the design
   a. What assumptions can we make?

   b. What constraints should we consider?

**Whole Class:**

9. How might you analyze the data?

   a. Now you are ready to begin calculating uncertainties associated with your experiment.
      i. When doing these calculations, make sure to show step by step how you get from the value to its uncertainty.

      ii. For what values in this experiment can you calculate uncertainties?

         a. What are the Measured uncertainties in this experiment?

         b. What are the Systematic errors in this experiment?

         c. Which Propagated uncertainties are associated with this experiment?

   b. What do the data indicate initially – does it look correct?

   c. What are you comparing?
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i. What data depends on other data (independent and dependent variables)?

ii. How can we use the uncertainties when comparing data?
   a. What values are we comparing?
   b. What are the uncertainties of these values?
   d. What observations did you make?

Groups:
10. Do calculations, uncertainties, graphs, and SETs in Excel

11. In this lab you will do a more formal Excel sheet.
   a. Please include the experiment name, today’s date, the names of students in your
group near the top of the excel page.

   b. When doing your calculations, graphs, and compared data, make sure these
   sections are organized and the data flows in a logical manner (such as placing the
measured/collected data first, calculations, and then the graphs).

12. Submit through In Class Analysis

Whole Class:
13. Did all of your initial questions get answered?
   a. If no, why not?

14. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

15. How could this experiment be used in real life?

Questions to be answered as part of your lab report:
1. Which would be more damaging: driving into a massive concrete wall, or driving at the
same speed into a head-on collision with an identical car traveling toward you at the same
speed?

2. A compressed spring is placed with a light adhesive between the large car and the small
car such that it is touching the facing ends. The binding of the spring is removed and the
two cars are thrust from each other with the spring no longer attached to either. What is
the ratio of the speed of the smaller car to that of the larger? Use numbers for the cars you
used in this experiment.

Turn in your Experimental Information Sheet to your TA before you leave class.

Submitting your In-Class Analysis through Blackboard opens a portal for you to be able to
submit your Lab Report. You are required to submit your lab report through Blackboard in order for it to be graded. It will be checked by a software program called WebAssign to check for cheating.

Submit your lab report within 6 days of the beginning of your lab (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).

Student Version SR-Focused – Winter 2012
Experiment 8: Angular Acceleration

Pre-lab
Please do the following BEFORE coming to your lab class:
- Read the background information provided on blackboard
- Take the quiz related to this lab
- Print off a copy of the laboratory write-up or use a specific notebook to keep track of your information for the labs

Learning Objectives:
Students should be able to:
- Understand the relationship between Newton’s Laws of Motion and rotational motion of a rigid body
- Define moment of inertia
- Understand that the moment of inertia is based on the shape and dimensions of its cross section
- Calculate moment of inertia for various rigid bodies, including a disk and ring

Equipment:
- Digital calipers
- 3-beam balance, with 1-kg add-on
- 9’ plastic disk
- 4’ steel ring
- Rotating platform base
- Rotary motion sensor
- Computer with Science Workshop interface

Experiment Information Sheet should contain:
- Experimental question(s) to be answered
- Design / Procedures
- Observations
- What data depends on other data (list both)
The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

Whole Class:
1. What questions are we trying to answer?
   a. What do you know about rotational motion?
   b. What do you know about moments of inertia?
   c. What do you know about torque?

2. How can we evaluate inertia?

Groups:
3. What method should be used to test angular acceleration given the equipment?
   a. What do we need to measure?
   b. What is given to us / can we consider any known values?

4. Now it is time to figure out how to test your method, called an experimental design.
   a. What are the independent and dependent variables?
   b. What variables should we control in this experiment?
   c. Discuss why you might want to use this design?
   d. How will it answer your questions?
   e. Is this a design that could easily be replicated by other scientists?
   f. Using this design, what is your hypothesis (a general statement), what do you predict (a more specific statement) will happen; how might it answer your questions?

Compare Designs between groups
Discuss as whole class - Decide which is best or if more than one is ok.

Groups:
5. What type of data is to be collected?
   a. Create chart in Excel
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6. Perform experiment, collect data
   a. Are there variations in the measurements, method or data collection?

7. Given the design
   a. What assumptions can we make?
   b. What constraints should we consider?

Whole Class:
8. How might you analyze the data?
   e. Now you are ready to begin calculating uncertainties associated with your experiment.
      i. When doing these calculations, make sure to show step by step how you get from the value to its uncertainty.
      ii. For what values in this experiment can you calculate uncertainties?
         a. What are the **Measured uncertainties** in this experiment?
         b. What are the **Systematic errors** in this experiment?
         c. Which **Propagated uncertainties** are associated with this experiment?
   f. What do the data indicate initially – does it look correct?
   g. What are you comparing?
      i. What data depends on other data (independent and dependent variables)?
      ii. How can we use the uncertainties when comparing data?
         a. What values are we comparing?
         b. What are the uncertainties of these values?
   h. What observations did you make?

Groups:
9. Do calculations, uncertainties, graphs, and SETs in Excel
10. In this lab you will do a more formal Excel sheet.
    c. Please include the experiment name, today’s date, the names of students in your group near the top of the excel page.
    d. When doing your calculations, graphs, and compared data, make sure these sections are organized and the data flows in a logical manner (such as placing the
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<tr>
<th>Question</th>
<th>Answer</th>
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<td>measured/collection data first, calculations, and then the graphs)</td>
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<td>11. Submit through In Class Analysis</td>
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<tr>
<td>Whole Class:</td>
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<tr>
<td>12. Did all of your initial questions get answered?</td>
<td></td>
</tr>
<tr>
<td>a. If no, why not?</td>
<td></td>
</tr>
<tr>
<td>13. What additional questions do you have that were not answered by doing the experiment?</td>
<td></td>
</tr>
<tr>
<td>a. What additional experiments could be done to answer these?</td>
<td></td>
</tr>
<tr>
<td>14. How could this experiment be used in real life?</td>
<td></td>
</tr>
<tr>
<td>Questions to be answered as part of your lab report:</td>
<td>Use moment of inertia to answer these questions.</td>
</tr>
<tr>
<td>1. A ramp is placed on a table top so that the bottom is hanging over the edge. A marble and a golf ball are released from rest at the same time on the ramp, at the same height. (The contact point for each is at the same height.) Assuming they roll straight down the ramp without slipping, following parallel paths, which reaches the bottom first? Or do they both reach the bottom at the same time? Why?</td>
<td></td>
</tr>
<tr>
<td>2. A filled cylindrical can and an empty can the same size are released from rest on the same ramp at the same height. Assuming they roll straight down the ramp without slipping, following parallel paths, which reaches the bottom first? Or do they both reach the bottom at the same time? Why?</td>
<td></td>
</tr>
</tbody>
</table>

Turn in your Experimental Information Sheet to your TA before you leave class.

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Submit your lab report within 6 days of the beginning of your lab (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).
Appendix D

SR-Focused Experiment Instructions Provided to TAs, includes Scaffolding

<table>
<thead>
<tr>
<th>TA Version – Spring 2012</th>
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</thead>
<tbody>
<tr>
<td>Experiment 1: <strong>Measurement and Uncertainty</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pre-lab</th>
<th>Please do the following BEFORE coming to your lab class:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Read the background information provided on blackboard</td>
</tr>
<tr>
<td></td>
<td>• Take the quiz related to this lab [Due 1 hour before lab class]</td>
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<td></td>
<td>• If you are able, print off a copy of this experiment write-up</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Learning Objectives:</th>
<th>Students should be able to:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Create an experimental design</td>
</tr>
<tr>
<td></td>
<td>• State measurement and units for length, mass and time.</td>
</tr>
<tr>
<td></td>
<td>• Recognize no measurement is exact</td>
</tr>
<tr>
<td></td>
<td>• Determine what may cause an uncertainty in a measurement</td>
</tr>
<tr>
<td></td>
<td>• Understand the general relationships between length of the pendulum and period (or time it takes to complete one swing)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equipment:</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>• Pendulum</td>
</tr>
<tr>
<td></td>
<td>• Stopwatch</td>
</tr>
<tr>
<td></td>
<td>• Computer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment Information Sheet should contain:</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>• Experimental question(s) to be answered</td>
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<td>• Observations</td>
</tr>
<tr>
<td></td>
<td>• What data depends on other data (list variables)</td>
</tr>
</tbody>
</table>

The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

**Whole Class:**  

1. **SCAFFOLDING: Discuss each of the following: Research, collaboration, measuring, concept of uncertainty, observation:**

   a. In this lab class you will learn about:

      i. **Research:** A systematic investigation, which provides knowledge for new ideas, solves problems, or develops new theories
ii. **Collaboration**: To work together with other researchers (students) in an intellectual endeavor toward a common goal

iii. **Making Measurement**: The act of determining the dimensions, capacity or amount of something

iv. **Concept of uncertainty**: A parameter associated with the doubt about the validity of the result of a measurement, which can be attributed to the instruments, design or researcher.

v. **Observation**: Anything you see, hear, smell, taste, or touch is an observation. Scientists obtain a great deal of the evidence they use by observing natural and experimentally generated objects and effects.

2. What questions are we trying to answer given the objectives of this experiment, the equipment and background information? These are called Research Questions.

   a. **PROMPT**: What else do you know about pendulum motion? *Length, period*

   b. Make sure that you write down your research question(s) on your Experiment Information Sheet.

3. Now it is time to figure out how to develop a method, called an experimental design, to test the research question(s).

   a. **SCAFFOLDING**: Creating an experimental design requires discussion between researchers (you, the students, are considered researchers in this class). You should consider different ideas for your testing method. *We will discuss this more as the quarter progresses.*

   b. First we need to collect some information. The following questions are included here to help you figure out your experimental design and what procedures to use as part of your test.

4. What does a pendulum do?

5. What type of data can you collect?

   a. **PROMPT**: Length of pendulum and time of swings
Reforming the intro physics lab to impact SR

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<tbody>
<tr>
<td>b.</td>
<td>What do we need to measure?</td>
</tr>
<tr>
<td>c.</td>
<td>What is given to us / can we consider any known values?</td>
</tr>
</tbody>
</table>

6. What can we compare?
   a. How can we evaluate the length of the pendulum without measuring it?

Groups:

1. What method should be used to test the period of a pendulum given the equipment?
   a. In this lab, we’ll give you some help at creating the design.
   b. Each group will measure 1 single swing and then measure multiple swings (choosing 3, 5 or 10 swings).
      i. Discuss why you might want to use this design?
      ii. How will it answer your questions (that you came up with in #2 above)?
      iii. Make sure that you write down the design you choose for this experiment on your Experiment Information Sheet.

2. Perform experiment, collect data
   a. Create a chart in Excel for the data you will measure / collect.
   b. Each group will measure 1 single swing at a small angle - about 10 degrees
      i. **PROMPT:** Explain that the pendulum should already be moving before recording the time for the period.
   c. Each group will take time measurements for a different number of swings (each group chooses one of the following):
      i. 3 swings (do this two times)
      ii. 5 swings (do this once)
      iii. 10 swings (do this once)

3. Given the design
   a. **SCAFFOLDING:** An assumption is something taken for granted or accepted as true without proof.
      i. What assumptions can we make in this experiment?
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| Whole Class: | 1. How can you get an uncertainty value (sometimes called errors) from this design?  
|             | a. Can errors occur in measurements? In other types of data collect?  
|             | 2. How might you analyze the data?  
|             | a. SCAFFOLDING: In order for us to tell if our data is good, we must look at it in different ways, or analyze it. Researchers will typically perform calculations relevant to the theory being tested and data collected; and, usually graph their data to look for trends and relationships. Data Analysis is what supports a research question. We will discuss how to analyze data in different manners throughout this lab course.  
|             | b. For today’s lab we will  
|             | i. Determine which calculations you may want to use  
|             | ii. Plot a graph called a histogram (see blackboard – Course Information, Useful Tutorials, Create a Histogram in Excel for how to do this)  
|             | iii. Visually compare our data  
|             | c. PROMPT:  
|             | i. Explain why it is important to do calculations with an experiment. Help the students with any relevant calculations.  
|             | ii. Explain to them what a histogram is and help them do it if they can’t figure it out (I have placed some information on blackboard for them)  
|             | iii. Review with students the concept of comparison of values.  
|             | d. What do the data indicate initially – does it look correct?  
|             | e. What are you comparing?  

b. SCAFFOLDING: A constraint is anything that limits the experiment. It can be internal or external and sources may include equipment, researchers or outside factors.  
   i. What constraints should we consider in this experiment?
Reforming the intro physics lab to impact SR

| i. What data depends on other data?
| --- |
| *SCAFFOLDING:* The data variable which is manipulated by the researcher is called an independent variable. While the data variable, which relies on the manipulated variable, is called a dependent variable. We will discuss this more in the next lab class.

| f. What observations did you make?
<table>
<thead>
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<tbody>
<tr>
<td>Groups:</td>
</tr>
<tr>
<td>1. Do calculations, histogram in Excel</td>
</tr>
<tr>
<td>a. PROMPT: If students struggle how to do calculations and the histogram in excel – explain/help as needed.</td>
</tr>
<tr>
<td>2. Submit Excel spreadsheet through In Class Analysis on Blackboard</td>
</tr>
<tr>
<td>Whole Class:</td>
</tr>
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<td>1. Did all of your initial questions get answered?</td>
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<td>a. If no, why not?</td>
</tr>
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<td>2. What additional questions do you have that were not answered by doing the experiment?</td>
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<tr>
<td>a. What additional experiments could be done to answer these?</td>
</tr>
<tr>
<td>3. How could this experiment be used in the real world?</td>
</tr>
</tbody>
</table>

Questions to be answered as part of your lab report:

1. Three different techniques are used to measure the diameter and circumference of a circular object in order to find pi experimentally. Method A resulted in $3.133 \pm 0.007$, Method B gave $3.1609 \pm 0.0002$, and the result of Method C was $3.14 \pm 0.03$. Which of these methods were the most accurate and which was the most precise? Why?

2. If you wanted to build a pendulum that took a long time to make a full swing, what would you have to do about the length?

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Reforming the intro physics lab to impact SR

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<tbody>
<tr>
<td><strong>Experiment 2:</strong> Data Graphics and Analysis</td>
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<tbody>
<tr>
<td></td>
<td>• Determine relationship between length and time as they relate to motion with constant acceleration.</td>
</tr>
<tr>
<td></td>
<td>• Determine the difference between independent and dependent variables; what variables are held constant as controls</td>
</tr>
<tr>
<td></td>
<td>• Understand how to use graphical representations in data analysis</td>
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<table>
<thead>
<tr>
<th>Equipment:</th>
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<tbody>
<tr>
<td></td>
<td>• Tape measure</td>
</tr>
<tr>
<td></td>
<td>• Adjustable length pendulum with stand</td>
</tr>
<tr>
<td></td>
<td>• Photogate</td>
</tr>
<tr>
<td></td>
<td>• Computer with Science Workshop interface</td>
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</tbody>
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<table>
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<tr>
<th>Experiment Information Sheet should contain:</th>
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<table>
<thead>
<tr>
<th>Whole Class:</th>
<th>1. REVIEW: Previously we discussed: Research, collaboration, making measurements, concept of uncertainty and observations. You also learned about: variables, assumption, constraints, research questions, collecting data and research designs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2. What questions are we trying to answer given the objectives of this</td>
</tr>
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</table>

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experiment, the equipment and background information? These are called Research Questions.

- **PROMPT:** What did we learn from last week’s lab?  
  Measuring, concept of uncertainty, period, pendulum motion.

  b. Make sure that you write down your research question(s) on your Experiment Information Sheet.

### Groups:

3. Now it is time to figure out how to develop a method, called an experimental design, to test the research question(s).

  a. Creating an experimental design requires discussion between researchers (you, the students are considered researchers in this class). You should consider different ideas for your testing method. We will discuss this more as the quarter progresses.

  b. **SCAFFOLDING:** Discuss the difference between independent and dependent variables:

  c. In this lab we will learn how to identify independent and dependent variables

  i. **Independent variables:** In any experimental design, a researcher will manipulate one type of data called the independent variable, and will study how it affects other types of data collected.

  1. What is the independent variable in this experiment?

  ii. **Dependent variables:** The other types of data (from above) affected by the independent variable are called dependent variables.

  1. What is the dependent variable(s) in this experiment?

  d. **SCAFFOLDING:** Discuss the importance of controlling variables:

  i. **How can we control variables?** A control variable is a variable that must not be changed throughout an experiment because it affects the dependent variables and thus affects the outcome of the experiment.

  1. What variables should we control in this experiment?

  e. First we need to collect some information. The following
questions are included here to help you figure out your experimental design and what procedures to use as part of your test.

4. How can we evaluate the relationship between the period of a pendulum and the length of a pendulum?

Whole Class:

1. What type of data can you collect?
   a. **PROMPT: Length of pendulum and time of swings**
   b. What do we need to measure?
   c. What is given to us / can we consider any known values?

2. What can we compare?

Groups:

1. What method should be used to test the period of a pendulum given the equipment?
   a. Last time we tested the times of various swings to find the length of the pendulum. How can we test the linear relationship of the variables?
      i. Discuss why you might want to use this design?
      ii. How will it answer your questions (that you came up with in #2 above)?
      iii. Make sure that you write down the design you choose for this experiment on your Experiment Information Sheet.

2. Perform experiment, collect data
   a. Create a chart in Excel for the data you will measure / collect.
   b. Are there variations in the measurements, method or data collection?

3. Given the design
   i. What assumptions can we make in this experiment?
   ii. What constraints should we consider in this experiment?

Whole Class:

1. How can you get an uncertainty value (sometimes called errors) from this design?
Reforming the intro physics lab to impact SR

| Groups: | 1. Do calculations, graph(s) in Excel  
|         |   a. PROMPT: If students struggle how to do calculations and graphs in excel – explain/help as needed.  
|         | 2. Submit Excel spreadsheet through In Class Analysis on Blackboard  
| Whole Class: | 1. Did all of your initial questions get answered?  
|             |   a. If no, why not?  
|             | 2. What additional questions do you have that were not answered by doing the experiment?  
|             |   a. What additional experiments could be done to answer these?  

| 2. How might you analyze the data?  
| a. SCAFFOLDING: Least square fit (and linest), trendline:  
|   i. Are there any calculations or graphs you might want to use?  
|   ii. In this lab you will learn how to perform a least squares fit: A mathematical procedure for finding the best-fitting line or curve to a given set of points by minimizing the sum of the squares of the errors made in solving each individual equation. Outlying points can have an effect on the fit, which may skew the fit line or curve. We call a linear fit a trendline.  
| b. Determine which calculations you may want to use  
| c. What do the data indicate initially – does it look correct?  
| d. What are you comparing?  
|   i. What data depends on other data?  
|   ii. State your variables here.  
| e. What observations did you make?  
| a. What uncertainties or errors might you have in this experiment?
Questions to be answered as part of your lab report:

1. Two students doing this experiment came up with a slope for \( l \) vs. \((T / 2\pi)^2\) of 9.86 ± 0.04 m/s². How does this compare with the value it should be? (Are the two values equivalent?) Why?

2. A simple pendulum is known to have a period of oscillation \( T = 1.55 \) s. Amy uses a digital stopwatch to measure the total time for 5 oscillations and calculate an average period of \( T = 1.25 \) s. Bob uses an analog wristwatch and the same procedure to calculate an average period for the 5 oscillations and finds \( T = 1.6 \) s. Which student made the more accurate measurement? Explain.

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Reforming the intro physics lab to impact SR

| Equipment:                  | Meter stick and 2-meter stick  |
|                            | Ball bearing                  |
|                            | Launcher for ball bearing     |
|                            | Landing pad                   |
|                            | Science Workshop interface    |
|                            | Computer                      |

| Experiment Information Sheet should contain: | Experimental question(s) to be answered |
|                                             | Design / Procedures              |
|                                             | Observations                     |
|                                             | What data depends on other data (list variables) |

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Whole Class: REVIEW:

1. Previously we discussed: Research, collaboration, making measurements, concept of uncertainty and observations.
2. You also learned about:
   a. variables, assumption, constraints, research questions, collecting data and research designs
   b. independent and dependent variables, control for variables, Least Squares Fit, Linest, trendline

3. What research questions are we trying to answer given the objectives of this experiment, the equipment and background information?
   a. Make sure that you write down your research question(s) on your Experiment Information Sheet.

Groups: 4. Discuss your options of an experimental design:

   a. **SCAFFOLDING:** Discuss the importance of prediction and replication:

      i. In this lab we will learn how to predict outcomes of the experiment and discuss why being able to replicate an experiment is important.

      1. Prediction: Your prediction lets you specifically state how you think your research questions will
Reforming the intro physics lab to impact SR

be answered. The experiment that you will design is done to test the prediction. Once you develop a prediction, you shouldn't change it, even if the results of your experiment show that you were wrong. An incorrect prediction does not mean that you "failed." It just means that the experiment brought some new facts to light that maybe you hadn't thought about before.

2. Replication: Confidence is added to results if an experiment is replicated by other researchers. This helps confirm that the previous results weren't dependent on some unreported aspect of the first experiment and that it wasn't the result of a statistical fluke or sloppy or fraudulent work. We are doing replication style experiments in this lab class.

<table>
<thead>
<tr>
<th>Whole Class:</th>
<th>5. How can we evaluate velocity, acceleration for a falling body?</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1. What type of data can you collect?</td>
</tr>
<tr>
<td></td>
<td>a. What do we need to measure?</td>
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<td></td>
<td>b. What is given to us / can we consider any known values?</td>
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<table>
<thead>
<tr>
<th>Groups:</th>
<th>1. What method(s) should be used to test free fall given the equipment?</th>
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<tbody>
<tr>
<td></td>
<td>a. What are the independent and dependent variables?</td>
</tr>
<tr>
<td></td>
<td>b. What variables should we control in this experiment?</td>
</tr>
<tr>
<td></td>
<td>c. Discuss why you might want to use this design?</td>
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<tr>
<td></td>
<td>d. How will it answer your questions?</td>
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<td></td>
<td>e. Is this a design that could easily be replicated by other scientists?</td>
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<td></td>
<td>f. Using this design, what do you predict will happen; what values</td>
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Reforming the intro physics lab to impact SR

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<tr>
<td><strong>g.</strong> Make sure that you write down the design you choose for this experiment on your <strong>Experiment Information Sheet.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>2.</strong> Perform experiment, collect data</td>
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</tr>
<tr>
<td>b. Create a chart in Excel for the data you will measure / collect.</td>
<td></td>
</tr>
<tr>
<td>c. Are there variations in the measurements, method or data collection?</td>
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</tr>
<tr>
<td><strong>3.</strong> Given the design</td>
<td></td>
</tr>
<tr>
<td>a. What assumptions can we make in this experiment?</td>
<td></td>
</tr>
<tr>
<td>b. What constraints should we consider in this experiment?</td>
<td></td>
</tr>
<tr>
<td><strong>Whole Class:</strong></td>
<td></td>
</tr>
<tr>
<td>1. What uncertainties or errors might you have in this experiment?</td>
<td></td>
</tr>
<tr>
<td>2. How might you analyze the data?</td>
<td></td>
</tr>
<tr>
<td>a. Determine which calculations you may want to use</td>
<td></td>
</tr>
<tr>
<td>b. We discussed independent and dependent variables earlier. How do you plot these on a graph?</td>
<td></td>
</tr>
<tr>
<td>i. Which axis do you place the dependent variable? The independent variable?</td>
<td></td>
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<tr>
<td>c. What do the data indicate initially – does it look correct?</td>
<td></td>
</tr>
<tr>
<td>d. What are you comparing?</td>
<td></td>
</tr>
<tr>
<td>i. What data depends on other data?</td>
<td></td>
</tr>
<tr>
<td>ii. State your variables here.</td>
<td></td>
</tr>
<tr>
<td>e. How can we use the uncertainties when comparing data?</td>
<td></td>
</tr>
<tr>
<td>i. <strong>SCAFFOLDING:</strong> Introduce <strong>SET here.</strong></td>
<td></td>
</tr>
<tr>
<td>1. <strong>One way we can show a comparison between experimental results and a given value is to calculate it through the Standard Equivalency Test (SET).</strong></td>
<td></td>
</tr>
<tr>
<td>2. <strong>SET is the mathematical test you use to compare two numbers that are supposed to be</strong></td>
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</table>

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equal. If the inequality is true, values $A$ and $B$ (below) are equivalent:

3. We show this by calculating: $A - B \leq \frac{\sqrt{u_A^2 + u_B^2}}{2}$, where $A$ is the theoretical or give value and $B$ is the experimental value. $A$ and $B$ by itself are the values, while the $u_A$ and $u_B$ are the uncertainties associated with the values.

f. What observations did you make?

<table>
<thead>
<tr>
<th>Groups:</th>
<th>1. Do calculations, graph(s) in Excel</th>
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</tr>
<tr>
<td></td>
<td>3. Submit Excel spreadsheet through In Class Analysis on Blackboard</td>
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</tbody>
</table>

| Whole Class: | 1. Did all of your initial questions get answered? |
|             | a. If no, why not? |
|             | 2. What additional questions do you have that were not answered by doing the experiment? |
|             | b. What additional experiments could be done to answer these? |
|             | 3. How could this experiment be used in the real world? |
Questions to be answered as part of your lab report:

1. A student decides to test the average acceleration of his iPod falling from the window of a room on the 3rd floor of Braunstein Hall. He uses a meter stick to measure the height and the stopwatch on his wristwatch to collect data. He finds for the 3 trials: heights = 5.25 m, 5.18 m, 5.23 m, times = 1.14 s, 1.19 s, 1.15 s. What is the average acceleration?

2. Is the diver below correct in his calculation? If he steps off that board, how fast in miles per hour would he be going when he hits the water? Show your work.

Is this guy really a whiz?

**Turn in your Experimental Information Sheet to your TA before you leave class.**

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**Submit your lab report within 6 days of the beginning of your lab** (for example if your lab starts at 10:30 am on Wednesdays, your lab report is due before 10:30 am on Tuesday).

**TA Version – Spring 2012**

**Experiment 4: Vector Forces**

<table>
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<tr>
<th>Pre-lab</th>
<th>Please do the following BEFORE coming to your lab class:</th>
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<tbody>
<tr>
<td></td>
<td>• Read the background information provided on blackboard</td>
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</table>
Reforming the intro physics lab to impact SR

<table>
<thead>
<tr>
<th>Learning Objectives:</th>
<th>Students should be able to:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>● State what a vector is and gain experience working with vectors</td>
</tr>
<tr>
<td></td>
<td>● Demonstrate the process of adding vectors</td>
</tr>
<tr>
<td></td>
<td>● Use two independent methods for demonstrating the relationship between vector addition and a resultant vector</td>
</tr>
<tr>
<td></td>
<td>● Determine how to make a prediction about an experiment</td>
</tr>
<tr>
<td></td>
<td>● Understand why replication of experiments is important</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equipment:</th>
</tr>
</thead>
<tbody>
<tr>
<td>● Colored pencils</td>
</tr>
<tr>
<td>● Drawing compass</td>
</tr>
<tr>
<td>● Protractor</td>
</tr>
<tr>
<td>● Drafting triangle</td>
</tr>
<tr>
<td>● Straightedge (ruler)</td>
</tr>
<tr>
<td>● Plain white paper</td>
</tr>
<tr>
<td>● Triple beam balance</td>
</tr>
<tr>
<td>● Force table with 4 pulleys</td>
</tr>
<tr>
<td>● Strings</td>
</tr>
<tr>
<td>● 4 Mass hangers</td>
</tr>
<tr>
<td>● Various slotted masses</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment Information Sheet should contain:</th>
</tr>
</thead>
<tbody>
<tr>
<td>● Experimental question(s) to be answered</td>
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<tr>
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</tr>
<tr>
<td>● Observations</td>
</tr>
<tr>
<td>● What data depends on other data (list variables)</td>
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The TA will begin class with a brief discussion, explanation of equipment (details of proper use, safety issues, etc.). You will work together as a class and in groups. There will be 4 students to a group. Although you should try to be as thorough as possible, it is ok if you don’t think of everything. That is why we will be comparing and discussing your designs and results.

<table>
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<th>Whole Class:</th>
<th>REVIEW:</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1. <strong>Previously we discussed:</strong> Research, collaboration, making measurements, concept of uncertainty and observations.</td>
</tr>
<tr>
<td></td>
<td>2. <strong>You also learned about:</strong></td>
</tr>
<tr>
<td></td>
<td>a. Variables, assumption, constraints, research questions, collecting data and research designs</td>
</tr>
<tr>
<td></td>
<td>b. Independent and dependent variables, control for variables, Least Squares Fit, Linest, trendline</td>
</tr>
</tbody>
</table>

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Reforming the intro physics lab to impact SR

c. Prediction and replication, SET

3. What research questions are we trying to answer given the objectives of this experiment, the equipment and background information?

4. This lab will have two experiments using vectors – a hand drawn graphical representation and an experiment with equipment where you collect data.

   a. Make sure that you write down your research question(s) on your Experiment Information Sheet.

Groups:

1. Discuss your options of an experimental design:

   b. SCAFFOLDING: Discuss the importance of prediction and replication:

      ii. In this lab we will learn how to predict outcomes of the experiment and discuss why being able to replicate an experiment is important.

      3. Prediction: Your prediction lets you specifically state how you think your research questions will be answered. The experiment that you will design is done to test the prediction. Once you develop a prediction, you shouldn't change it, even if the results of your experiment show that you were wrong. An incorrect prediction does not mean that you "failed." It just means that the experiment brought some new facts to light that maybe you hadn't thought about before.

      4. Replication: Confidence is added to results if an experiment is replicated by other researchers. This helps confirm that the previous results weren't dependent on some unreported aspect of the first experiment and that it wasn't the result of a statistical fluke or sloppy or fraudulent work. We are doing replication style experiments in this lab class.

         a. Now collect information to help you figure out your experimental design.

2. How can we evaluate vector forces in 2 dimensions?
Reforming the intro physics lab to impact SR

| Whole Class: | 1. What type of data can you collect?  
|             | a. What do we need to measure?  
|             | b. What is given to us / can we consider any known values?  
|             | 2. What can we compare?  
| Groups:     | 1. What method(s) should be used to test free fall given the equipment?  
|             | a. What are the independent and dependent variables?  
|             | b. What variables should we control in this experiment?  
|             | c. Discuss why you might want to use this design?  
|             | d. How will it answer your questions?  
|             | e. Is this a design that could easily be replicated by other scientists?  
|             | f. Using this design, what do you predict will happen; what values will we obtain?  
|             | g. Make sure that you write down the design you choose for this experiment on your Experiment Information Sheet.  
|             | 2. Perform experiment, collect data  
|             | a. Create a chart in Excel for the data you will measure / collect.  
|             | b. Are there variations in the measurements, method or data collection?  
|             | 3. Given the design  
|             | a. What assumptions can we make in this experiment?  
|             | b. What constraints should we consider in this experiment?  
| Whole Class: | 1. What uncertainties or errors might you have in this experiment?  
|             | 2. How might you analyze the data?  
|             | a. Determine which calculations you may want to use  
|             | b. Show your experimental results on a hand drawn graph. This will
verify what you have come up with in your experiment.

i. Using a scaled down version of your vectors, draw the 4 vectors on a sheet of white paper.

ii. Add the 4 vectors together to get your final net force on the system.
   a. Use either the triangular method or parallelogram method for adding vectors.
   b. Draw the final force vector.
   c. What do the data indicate initially – does it look correct?
   d. What are you comparing?
      iii. What data depends on other data?
      iv. State your variables here.
   e. How can we use the uncertainties when comparing data?

iii. **SCAFFOLDING: Remind about SET.**

1. **One way we can show a comparison between experimental results and a given value is to calculate it through the Standard Equivalency Test (SET).**

2. **SET is the mathematical test you use to compare two numbers that are supposed to be equal. If the inequality is true, values A and B (below) are equivalent:**

3. **We show this by calculating: \( A - B \leq \frac{2}{2} \left( u_A \right)^2 + \left( u_B \right)^2, \) where A is the theoretical or give value and B is the experimental value. A and B by itself are the values, while the \( u\{A\} \) and \( u\{B\} \) are the uncertainties associated with the values.

f. What observations did you make?

| Groups: | 1. Do calculations, graph(s) in Excel |
2. In this lab you will do a more formal Excel sheet.
   c. Please include the experiment name, today’s date, the names of students in your group near the top of the excel page.
   d. When doing your calculations, graphs, and compared data, make sure these sections are organized and the data flows for the grader (such as placing the measured/collected data first, calculations, and then the graphs).

3. Submit Excel spreadsheet through In Class Analysis on Blackboard

### Whole Class:

1. Did all of your initial questions get answered?
   a. If no, why not?

2. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

3. How could this experiment be used in the real world?

### Questions to be answered as part of your lab report:

1. If all the hangers have the same mass, is it possible to neglect their weights because their contributions “cancel out” when the vector forces representing the string tensions are added together? Explain

2. Throughout this experiment, we have used the units “grams” to express the magnitude of the forces acting, and yet we know grams measure mass and not force. How can we do this, i.e., how can we be sure that the laws of vector addition are being validly tested?

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<tr>
<td></td>
<td>• State Newton’s Laws of Motion</td>
</tr>
<tr>
<td></td>
<td>• Analyze situations in which an object moves with constant velocity:</td>
</tr>
<tr>
<td></td>
<td>o Under the influence of gravity</td>
</tr>
<tr>
<td></td>
<td>o Under the influence of several forces</td>
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<tr>
<td></td>
<td>• Understand the relation between the force that acts on an object and the resulting change in the object’s velocity.</td>
</tr>
<tr>
<td></td>
<td>• Identify the relationship between force and acceleration</td>
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<tr>
<td></td>
<td>• Metric tape measure</td>
</tr>
<tr>
<td></td>
<td>• Digital calipers</td>
</tr>
<tr>
<td></td>
<td>• Triple beam balance</td>
</tr>
<tr>
<td></td>
<td>• Air track</td>
</tr>
<tr>
<td></td>
<td>• Various aluminum blocks</td>
</tr>
<tr>
<td></td>
<td>• 2 cars (gliders) of unequal mass with flags (aluminum inserts on top)</td>
</tr>
<tr>
<td></td>
<td>• Piece of string with tied loops at both ends</td>
</tr>
<tr>
<td></td>
<td>• Fishing bob</td>
</tr>
<tr>
<td></td>
<td>• Photogate</td>
</tr>
<tr>
<td></td>
<td>• Computer with Science Workshop interface</td>
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Reforming the intro physics lab to impact SR

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<td>b. We discussed previously how to make a prediction about your results. Now you will make a formal statement called a hypothesis.</td>
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<td>i. <strong>Hypothesis</strong> basically means &quot;a possible solution to a problem, based on knowledge and research.&quot; The hypothesis is a simple (general) statement that defines what you think the outcome of your experiment will be.</td>
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<td>c. Now collect information to help you figure out your experimental design.</td>
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<thead>
<tr>
<th>2. How can we evaluate an object moving down an inclined plane?</th>
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</thead>
<tbody>
<tr>
<td>a. Under gravity?</td>
</tr>
<tr>
<td>b. Under an accelerating force?</td>
</tr>
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<tr>
<th>3. What do we know about tension?</th>
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</thead>
<tbody>
<tr>
<td>a. How does acceleration change when an object is subject to a tension force?</td>
</tr>
</tbody>
</table>

| Whole | 4. What type of data can you collect? |
### Reforming the intro physics lab to impact SR

| Class: | a. What do we need to measure?  
|        | b. What is given to us / can we consider any known values?  
|        | 5. What can we compare?  |
| Groups: | 1. What method(s) should be used to test free fall given the equipment?  
|         | h. What are the independent and dependent variables?  
|         | i. What variables should we control in this experiment?  
|         | j. Discuss why you might want to use this design?  
|         | k. How will it answer your questions?  
|         | l. Is this a design that could easily be replicated by other scientists?  
|         | m. Using this design  
|         | i. What is your hypothesis (a general statement)?  
|         | ii. What do you predict will happen?  
|         | iii. What values will we obtain?  |
|         | 2. Make sure that you write down the design you choose for this experiment on your Experiment Information Sheet.  |
|         | 3. Perform experiment, collect data  
|         | c. Create a chart in Excel for the data you will measure / collect.  
|         | d. Are there variations in the measurements, method or data collection?  |
|         | 4. Given the design  
|         | c. What assumptions can we make in this experiment?  
|         | d. What constraints should we consider in this experiment?  |
| Whole Class: | 1. What uncertainties or errors might you have in this experiment?  
|             | 2. How might you analyze the data? |
 Reforming the intro physics lab to impact SR

a. **PROMPT**: Help students with the following as necessary: Calculations, uncertainties, graphs, comparison of values

b. **SCAFFOLDING**: Introduce that we can separate uncertainties into categories and that some can be calculated. Explain why we do this.

c. We have discussed the concept of uncertainty in measurements. Now we need to learn the different types of uncertainties (sometimes called errors).

   i. Random uncertainties occur due to slightly different measuring conditions and to disparate observer interpretations.

   ii. Measured uncertainties are considered random uncertainties: A quantity associated with the doubt about the validity of the result of a measurement. This means that if you measure a weight of 34.7 grams with an uncertainty (or doubt) of 0.3 grams, then we are saying the measurement is probably in the range of 34.4 g to 35.0 g. Therefore we would show our result as 34.7 ± 0.3 g. We represent the uncertainty as \( u_m = 0.3 \) g – where the ‘m’ is whatever value is being measured – so m would be mass here; you would use \( x \) for distance, \( t \) for time, etc.

   iii. Systematic errors: These uncertainties are due to conditions which are not taken into account during the experiment. They are reproducible and you may be able to compensate for them, if you recognize their affects on your results.

      1. These types of errors may also be due to assumptions or constraints that were made in the experiment

      2. Usually when discussing systematic errors we state what condition is affecting the results and how it may affect the results.

   iv. Propagated uncertainties: This is a process of determining an uncertainty through a calculation.

d. Determine which calculations you may want to use
e. We discussed independent and dependent variables earlier. How do you plot these on a graph?

   iii. Which axis do you place the dependent variable? The independent variable?

f. What do the data indicate initially – does it look correct?

g. What are you comparing?

   v. What data depends on other data?

   vi. State your variables here.

   vii. Is it appropriate to calculate the comparison with a Standard Equivalency Test (SET)?

h. What observations did you make?

Groups:

1. Do calculations, graph(s) in Excel
   a. **PROMPT:** You may need to do an example calculation of uncertainty for students.
   b. **PROMPT:** Discuss with students the equations to use and explain if they don’t already have them/understand:
      1. Velocity squared
      2. The length of the flag
      3. Acceleration – both theoretical and experimental

2. In this lab you will do a more formal Excel sheet.
   a. Please include the experiment name, today’s date, the names of students in your group near the top of the excel page.
   b. When doing your calculations, graphs, and compared data, make sure these sections are organized and the data flows for the grader (such as placing the measured/colllected data first, calculations, and then the graphs).

3. Submit Excel spreadsheet through In Class Analysis on Blackboard

Whole Class:

1. Did all of your initial questions get answered?
   b. If no, why not?

2. What additional questions do you have that were not answered by doing the experiment?
Reforming the intro physics lab to impact SR

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<table>
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<tbody>
<tr>
<td>c. What additional experiments could be done to answer these?</td>
<td></td>
</tr>
<tr>
<td>3. How could this experiment be used in the real world?</td>
<td></td>
</tr>
</tbody>
</table>

Questions to be answered as part of your lab report:

1. If the string used to connect the small weight to the car in Part 2 had appreciable mass, would the car still undergo uniform acceleration? Explain.

2. The experimental value of the acceleration depends differently on the mass of the car for the first force than it does for the second force. Explain how this difference comes about.

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TA Version – Spring 2012
Experiment 6: Centripetal Force

Pre-lab | Please do the following BEFORE coming to your lab class:
---|---
* Read the background information provided on blackboard  
* Take the quiz related to this lab [Due 1 hour before lab class]  
* If you are able, print off a copy of this experiment write-up

Learning Objectives: | Students should be able to:
---|---
* Determine the relationship between radius and angular velocity  
* Understand acceleration and force when an object moves in a curved path  
* Determine how to make a hypothesis  
* Determine how to control variables
Reforming the intro physics lab to impact SR

- Understand how to perform calculations of uncertainties
- Identify comparisons between results and theoretical or given values and analyze the comparisons

<table>
<thead>
<tr>
<th>Equipment:</th>
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</thead>
</table>
| - 3-beam balance  
- Rotating platform with base, rotary motion sensor, and motor  
- Mass hanger  
- Leader power supply and banana leads  
- Computer with Science Workshop interface |

<table>
<thead>
<tr>
<th>Experiment Information Sheet should contain:</th>
</tr>
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</table>
| - Experimental question(s) to be answered  
- Design / Procedures  
- Observations  
- What data depends on other data (list variables) |

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**Whole Class:**

**REVIEW:**

1. **Previously we discussed:** Research, collaboration, making measurements, concept of uncertainty and observations.

2. **You also learned about:**
   a. Variables, assumption, constraints, research questions, collecting data and research designs
   b. Independent and dependent variables, control for variables, Least Squares Fit, Lineset, trendline
   c. Prediction and replication, SET
   d. How to write a hypothesis; types of uncertainties: Random, measured, propagated and systematic errors.

3. What research questions are we trying to answer given the objectives of this experiment, the equipment and background information?
   a. What else do you know about springs?
      i. **PROMPT:** Introduce Hooke’s Law
   b. What else do you know about moving objects?
      i. **PROMPT:** Briefly discuss acceleration, velocity
   c. Make sure that you write down your research question(s) on
### Groups:

1. Discuss your options of an experimental design:
   a. **SCAFFOLDING**: Explain what a hypothesis is and how to control variables:
   b. We discussed previously how to make a prediction about your results. Now you will make a formal statement called a hypothesis.
   
   i. **Hypothesis** basically means "a possible solution to a problem, based on knowledge and research." The hypothesis is a simple (general) statement that defines what you think the outcome of your experiment will be.
   c. Now collect information to help you figure out your experimental design.

2. How can we evaluate uniform circular motion?
   a. **PROMPT**: Discuss circular motion, period, angular velocity

3. What do we know about tension?
   a. How does acceleration change when an object is subject to a tension force?

### Whole Class:

1. What type of data can you collect?
   a. What do we need to measure?
   b. What is given to us / can we consider any known values?
   i. **PROMPT**: Explain radius and period

2. What can we compare?

### Groups:

1. What method(s) should be used to test free fall given the equipment?
   a. What are the independent and dependent variables?
   b. What variables should we control in this experiment?
   c. Discuss why you might want to use this design?
   d. How will it answer your questions?
   e. Is this a design that could easily be replicated by other
### Reforming the intro physics lab to impact SR

<table>
<thead>
<tr>
<th>Scientists?</th>
</tr>
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<tbody>
<tr>
<td>f. Using this design</td>
</tr>
<tr>
<td>i. What is your hypothesis (a general statement)?</td>
</tr>
<tr>
<td>ii. What do you predict will happen?</td>
</tr>
<tr>
<td>iii. What values will we obtain?</td>
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2. **Make sure that you write down the design you choose for this experiment on your Experiment Information Sheet.**

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<th>Perform experiment, collect data</th>
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<tr>
<td>a. Create a chart in Excel for the data you will measure / collect.</td>
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<tr>
<td>b. Are there variations in the measurements, method or data collection?</td>
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</table>

4. Given the design |
| a. What assumptions can we make in this experiment? |
| b. What constraints should we consider in this experiment? |

**Whole Class:**

1. What uncertainties or errors might you have in this experiment?

2. How might you analyze the data?

   a. **PROMPT:** Help students with the following as necessary: Calculations, uncertainties, graphs, comparison of values

   b. **SCAFFOLDING:** Remind students that we can separate uncertainties into categories and that some can be calculated. Explain why we do this.

   c. **We have discussed the concept of uncertainty in measurements. Now we need to learn the different types of uncertainties (sometimes called errors).**

      i. Random uncertainties occur due to slightly different measuring conditions and to disparate observer interpretations.

      ii. Measured uncertainties are considered random
uncertainties: A quantity associated with the doubt about the validity of the result of a measurement. This means that if you measure a weight of 34.7 grams with an uncertainty (or doubt) of 0.3 grams, then we are saying the measurement is probably in the range of 34.4 g to 35.0 g. Therefore we would show our result as 34.7 ± 0.3 g. We represent the uncertainty as \( u_m = 0.3 \text{ g} \) – where the ‘m’ is whatever value is being measured – so m would be mass here; you would use x for distance, t for time, etc.

iii. Systematic errors: These uncertainties are due to conditions which are not taken into account during the experiment. They are reproducible and you may be able to compensate for them, if you recognize their affects on your results.

1. These types of errors may also be due to assumptions or constraints that were made in the experiment
2. Usually when discussing systematic errors we state what condition is affecting the results and how it may affect the results.

iv. Propagated uncertainties: This is a process of determining an uncertainty through a calculation.

d. Determine which calculations you may want to use

e. We discussed independent and dependent variables earlier. How do you plot these on a graph?

iv. Which axis do you place the dependent variable? The independent variable?

f. What do the data indicate initially – does it look correct?

g. What are you comparing?

i. What data depends on other data?

ii. State your variables here.

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h. What observations did you make?
Reforming the intro physics lab to impact SR

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<td>3. How could this experiment be used in the real world?</td>
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Questions to be answered as part of your lab report:

1. Why is it crucial that the string from the mass to the pulley is purely horizontal and that the support string hangs straight up and down?

2. When the radius is increased, does the period of the circular motion increase or decrease? Explain.

**Turn in your Experimental Information Sheet to your TA before you leave class.**

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<td></td>
<td>● Define Conservation Laws</td>
</tr>
<tr>
<td></td>
<td>● Distinguish between elastic and inelastic collisions in 1-dimension</td>
</tr>
<tr>
<td></td>
<td>● Understand linear momentum, so they can:</td>
</tr>
<tr>
<td></td>
<td>○ Explain how linear momentum conservation follows as a consequence of Newton’s Third Law for an isolated system</td>
</tr>
<tr>
<td></td>
<td>● Understand conservation of energy, so they can:</td>
</tr>
<tr>
<td></td>
<td>○ Identify situations in which mechanical energy is or is not conserved</td>
</tr>
<tr>
<td></td>
<td>○ Describe situations in which mechanical energy is converted to other forms of energy</td>
</tr>
</tbody>
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<thead>
<tr>
<th>Equipment:</th>
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<tbody>
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<td></td>
<td>● Digital calipers</td>
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<tr>
<td></td>
<td>● Triple beam balance</td>
</tr>
<tr>
<td></td>
<td>● Air track</td>
</tr>
<tr>
<td></td>
<td>● 2 differently sized air track cars (gliders)</td>
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<td></td>
<td>● 2 photogates</td>
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<td></td>
<td>● Computer with Science Workshop interface</td>
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<th>Experiment Information Sheet should contain:</th>
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<td></td>
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<td>● Observations</td>
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<td>● What data depends on other data (list variables)</td>
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Reforming the intro physics lab to impact SR

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Whole Class: REVIEW:

1. Previously we discussed: Research, collaboration, making measurements, concept of uncertainty and observations.

2. You also learned about:
   a. Variables, assumption, constraints, research questions, collecting data and research designs
   b. Independent and dependent variables, control for variables, Least Squares Fit, Linest, trendline
   c. Prediction and replication, SET
   d. How to write a hypothesis; types of uncertainties: Random, measured, propagated and systematic errors.

3. What research questions are we trying to answer given the objectives of this experiment, the equipment and background information?
   a. PROMPT: Have them discuss the differences between momentum, mechanical and kinetic energies, and collisions in 1 dimension.
   b. What do you know about momentum?
   c. What do you know about mechanical and kinetic energies?
   d. What do you know about collisions in 1 dimension?
   e. Make sure that you write down your research question(s) on your Experiment Information Sheet.

Groups:

1. Discuss your options of an experimental design:
   PROMPT: Have students test both elastic and inelastic collisions – help them keep their designs simple using the two different cars.
   a. Now collect information to help you figure out your experimental design.

2. How can we evaluate elastic collisions?

3. How can we evaluate inelastic collisions?
Reforming the intro physics lab to impact SR

| Whole Class: | 1. What type of data can you collect?  
|             | a. What do we need to measure?  
|             | b. What is given to us / can we consider any known values?  
|             | 2. What can we compare?  
| Groups:     | 1. What method(s) should be used to test free fall given the equipment?  
|             | a. What are the independent and dependent variables?  
|             | b. What variables should we control in this experiment?  
|             | c. Discuss why you might want to use this design?  
|             | d. How will it answer your questions?  
|             | e. Is this a design that could easily be replicated by other scientists?  
|             | f. Using this design  
|             |   i. What is your hypothesis (a general statement)?  
|             |   ii. What do you predict will happen?  
|             |   iii. What values will we obtain?  
|             | 2. Make sure that you write down the design you choose for this experiment on your Experiment Information Sheet.  
|             | 3. Perform experiment, collect data  
|             | a. Create a chart in Excel for the data you will measure / collect.  
|             | b. Are there variations in the measurements, method or data collection?  
|             | 4. Given the design  
|             | a. What assumptions can we make in this experiment?  
|             | b. What constraints should we consider in this experiment?  

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Reforming the intro physics lab to impact SR

<table>
<thead>
<tr>
<th>Whole Class:</th>
<th>1. What uncertainties or errors might you have in this experiment?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2. How might you analyze the data?</td>
</tr>
<tr>
<td></td>
<td><strong>a. PROMPT: Assist students with the following as necessary:</strong> Calculations, uncertainties, graphs, comparison of values</td>
</tr>
<tr>
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<td>b. Determine which calculations you may want to use</td>
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<td></td>
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<td>f. What observations did you make?</td>
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<tr>
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<td>i. When doing these calculations, make sure to show step by step how you get from the value to its uncertainty.</td>
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<tr>
<td></td>
<td>ii. For what values in this experiment can you calculate uncertainties?</td>
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<tr>
<td></td>
<td>a. What are the Measured uncertainties in this experiment?</td>
</tr>
<tr>
<td></td>
<td>b. What are the Systematic errors in this experiment?</td>
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2. In this lab you will do a more formal Excel sheet.
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   b. When doing your calculations, graphs, and compared data, make sure these sections are organized and the data flows for the grader (such as placing the measured/collected data first, calculations, and then the graphs).

3. Submit Excel spreadsheet through In Class Analysis on Blackboard

**Whole Class:**

1. Did all of your initial questions get answered?
   a. If no, why not?

2. What additional questions do you have that were not answered by doing the experiment?
   a. What additional experiments could be done to answer these?

3. How could this experiment be used in the real world?

**Questions to be answered as part of your lab report:**

1. Which would be more damaging: driving into a massive concrete wall, or driving at the same speed into a head-on collision with an identical car traveling toward you at the same speed?

2. A compressed spring is placed with a light adhesive between the large car and the small car such that it is touching the facing ends. The binding of the spring is removed and the two cars are thrust from each other with the spring no longer attached to either. What is the ratio of the speed of the smaller car to that of the larger? Use numbers for the cars you used in this experiment.

*Turn in your Experimental Information Sheet to your TA before you leave class.*

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Reforming the intro physics lab to impact SR

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<th>Experiment 8:  Angular Acceleration</th>
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<td></td>
<td>• Understand the relationship between Newton’s Laws of Motion and</td>
</tr>
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<td></td>
<td>rotational motion of a rigid body</td>
</tr>
<tr>
<td></td>
<td>• Define moment of inertia</td>
</tr>
<tr>
<td></td>
<td>• Determine the relationship between torque and period</td>
</tr>
<tr>
<td>Equipment:</td>
<td>Digital calipers</td>
</tr>
<tr>
<td></td>
<td>3-beam balance, with 1-kg add-on</td>
</tr>
<tr>
<td></td>
<td>9’ plastic disk</td>
</tr>
<tr>
<td></td>
<td>4’ steel ring</td>
</tr>
<tr>
<td></td>
<td>Rotating platform base</td>
</tr>
<tr>
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### Whole Class: **REVIEW:**

1. **Previously we discussed:** Research, collaboration, making measurements, concept of uncertainty and observations.

2. **You also learned about:**
   - a. Variables, assumption, constraints, research questions, collecting data and research designs
   - b. Independent and dependent variables, control for variables, Least Squares Fit, Linest, trendline
   - c. Prediction and replication, SET
   - d. How to write a hypothesis; types of uncertainties: Random, measured, propagated and systematic errors.

3. What research questions are we trying to answer given the objectives of this experiment, the equipment and background information?

4. **PROMPT:** You may need to introduce rotational motion, moments of inertia – as they may not yet have the info from lecture.

   **PROMPT:** Show students how to use the additional 1 kg weight on the balance. Show how to properly use calipers if they don’t know.
   
   a. What do you know about rotational motion?
   
   b. What do you know about moments of inertia?
   
   c. What do you know about torque?
   
   d. Make sure that you write down your research question(s) on your Experiment Information Sheet.

### Groups:

1. Discuss your options of an experimental design:

   **PROMPT:** Have students include in their design the disk by itself and the disk plus the ring together. They should try different weights to start the system in motion.

   a. Now collect information to help you figure out your experimental design.

2. How can we evaluate inertia?

   a. **PROMPT:** Give information on inertia for a disk and ring; torque. Remind them about friction and acceleration and pulleys.
| Whole Class: | 1. What type of data can you collect?  
  |   | a. What do we need to measure?  
  |   | b. What is given to us / can we consider any known values?  
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  |   | iii. What values will we obtain?  
  |   | 2. Make sure that you write down the design you choose for this experiment on your Experiment Information Sheet.  
  |   | 3. Perform experiment, collect data  
  |   | PROMPT: Make sure the system spins in clockwise direction  
  |   | a. Create a chart in Excel for the data you will measure / collect.  
  |   | b. Are there variations in the measurements, method or data collection?  
  | 4. Given the design  
  |   | a. What assumptions can we make in this experiment?
Reforming the intro physics lab to impact SR

**Whole Class:**

1. What uncertainties or errors might you have in this experiment?

2. How might you analyze the data?

   - **PROMPT: Assist students with the following as necessary:**
     - Calculations, uncertainties, graphs, comparison of values

   - b. Determine which calculations you may want to use

   - c. We discussed independent and dependent variables earlier. How do you plot these on a graph?
     - i. Which axis do you place the dependent variable? The independent variable?

   - d. What do the data indicate initially – does it look correct?

   - e. What are you comparing?
     - i. What data depends on other data?
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     - iii. Is it appropriate to calculate the comparison with a Standard Equivalency Test (SET)?

   - f. What observations did you make?

**Groups:**

1. Do calculations, graph(s) in Excel

   - a. When doing these calculations, make sure to show step by step how you get from the value to its uncertainty.

   - b. For what values in this experiment can you calculate uncertainties?

   - c. What are the **Measured uncertainties** in this experiment?

   - d. What are the **Systematic errors** in this experiment?

   - e. Which **Propagated uncertainties** are associated with this experiment?

   - **PROMPT: Discuss with students the equations to use and**
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### Questions to be answered as part of your lab report:

1. A ramp is placed on a table top so that the bottom is hanging over the edge. A marble and a golf ball are released from rest at the same time on the ramp, at the same height. (The contact point for each is at the same height.) Assuming they roll straight down the ramp without slipping, following parallel paths, which reaches the bottom first? Or do they both reach the bottom at the same time? Why?

2. A filled cylindrical can and an empty can the same size are released from rest on the same ramp at the same height. Assuming they roll straight down the ramp without slipping, following parallel paths, which reaches the bottom first? Or do they both reach the bottom at the same time? Why?

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Appendix E

Traditional Experiment Instructions

Measurement and Uncertainty (last updated December 27, 2011)

Dr. Larry Bortner

Learning Objectives

Calculate basic laboratory statistics and explain their physical interpretations.

Perform calculations using Excel.

Propagate the uncertainty of a quantity calculated with uncertain values.

Determine if two uncertain values are equivalent.

Purpose

To use a pendulum to demonstrate the random nature of a physical measurement. To examine experimental methods that can decrease the uncertainty.

Background

The Pendulum

The period of a simple pendulum is the time it takes to make one complete cycle, or swing. Galileo noticed that this physical quantity was independent of both the amplitude (size) of the swing and of the mass of the bob. For small swings, the period $T$ of a pendulum of length $l$ is given by

$$T = 2\pi \sqrt{\frac{l}{g}}$$

(1)

where $g = 9.80 \text{ m/sec}^2 = 980 \text{ cm/sec}^2$ is the acceleration of gravity. (This is exact to 3 s.f. if the angle of the swing is < 5°.) When the pendulum swings, there is one true value of the period, which remains the same even as size of the swing changes. Any attempted measurement of this quantity will only be an approximation of the true value, no matter how precise the instrumentation. If we measure the period two different ways, those two approximate values may not exactly equal the true value but they should be close, and they should be close to each other.

Rearranging Eq. 2, we can express the length of a pendulum as

$$l = g \frac{T}{2\pi}^2$$

(2)
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In this experiment we assume that Eq. 2 is true and that \( g = 980 \text{ cm/sec}^2 \). Using a measured period \( T \), the calculated length should be the same as the measured length.

**Measurement and Uncertainty**

*What follows is a brief summary of pertinent material in Appendices 1 and 2. Refer to them for more details.*

In these physics labs we use \( u\{x\} \) to indicate the numerical uncertainty of a physical quantity \( x \), which can be either a measurement or a calculation. E.g., \( u\{x\} = 0.2 \text{ cm} \) means that the “fuzziness” of the way we are measuring \( x \) is 0.2 cm. If we measure \( x \) to be 34.7 cm, we’re saying it’s probably in the range of 34.5 cm to 34.9 cm.

No measurement of a continuous physical variable is exact. Some degree of uncertainty or error is associated with the measured data of all experiments. It follows that any calculation involving one or more measurements also has some degree of uncertainty. The process of deriving an expression to calculate this doubt is called the propagation of uncertainty. The details of this are given below.

Outside of blatant mistakes, we classify errors that occur in the data-collection process in two ways, either as random or systematic. Random uncertainties occur due to slightly different measuring conditions and to disparate observer interpretations. Systematic errors occur when there is a disconnect between the theory and experiment. They exist because of conditions not taken into account, are reproducible, and can sometimes be compensated for.

One way to find the random error in a particular measurement is to measure the same quantity many times in the same manner. The higher the number of trials, the closer the average gets to the true value (assuming no systematic errors and a normal distribution of errors about this true value).

- The standard deviation \( \sigma_x \) of a set of values \( x \) is a measure of the average variation of the individual measurements from the true value.
  - The physical interpretation of the standard deviation is that it is the error associated with any single measurement using a specific technique.

- The standard error \( \sigma_x \) of a set of values with an average \( x \) is calculated by dividing the standard deviation by the square root of the number of trials.
  - Physically it is the error associated with the average measurement. \( \sigma_x = u\{x\} \)

A histogram is a plot of the number of measurements that occur in a certain interval versus the average value of the intervals. An example histogram would be to record the height to the nearest inch of everyone in a large class, count the number of people who were at each height, then plot that count versus the height.

The functional relationship between the number and the average of the interval is called the distribution. If the distribution is normal, the peak of the resulting bell-shaped curve occurs at the average measurement value. The width of a normal curve at half its maximum is twice the standard deviation.
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We can use these concepts to improve the results of an experiment. Consider what we’ll measure today: the period of a pendulum. (Note that except for the two extremes, the pendulum bob passes through each position in the path twice in a complete swing.) The first measurement method is the obvious: measure the time it takes for the pendulum bob to go through one complete swing. Call this experimental technique the single swing timing (SST) technique.

We make one measurement. Are we through? How certain are we of that number we see on the stopwatch? That is, what is the uncertainty in this measurement? Certainly the error is no smaller than 0.01 seconds, the resolution of the instrument. Could it possibly be larger?

The hallmark of experimentation is repeatability. Say we measure the single swing time a total of ten times and find the average and standard deviation of those ten numbers. As long as we didn’t change the length or go wild with the swing size, we don’t expect the true period to change. According to the laws of statistics, if we time another single swing, there’s about a 68% chance that eleventh time will fall within the standard deviation of the average of our ten measurements. Here’s the cool thing: If we were to take 100 or 1000 similar times, the standard deviation would not appreciably change. The average would certainly get more precise (the standard error would get smaller), but the inherent accuracy of the SST method in a single measurement does not change just because you take more measurements.

As an aside, note that accuracy is how close a number is to the actual value, while precision is how many significant figures you can confidently state.

Making these ten measurements of the pendulum’s period gives us a precision to associate with the SST technique. Assume that the uncertainty comes in the starting and stopping of the watch. This means that the uncertainty is independent of the time interval we are measuring. If we were doing an experiment where we found the period for many lengths using the SST, we would only have to make single measurements for the remaining lengths since the uncertainty established for the period for one length is the same as for the period of any other length.

What if the precision isn’t good enough? Suppose the standard deviation is a larger error than we want to settle for. Can we make it smaller? Making more measurements would decrease the standard error but not the standard deviation, so we could just measure the period for each length ten times and forget about the single measurement. Let’s go with this idea but tweak it a bit.

Assuming that the period is independent of the amplitude, change the measurement to nine swing timing (NST). The following defines this technique:

- Make one measurement of the time for nine swings instead of a single swing.
- This elapsed time that you record is not the period. It is time that should be nine times larger than the period. To get the time for one swing, divide the measured time by nine. This calculation (as opposed to a straight measurement) is the period.
- To find the uncertainty of the NST method, repeat the timing nine more times (for a total of ten) at the same length. In your analysis, find the average and standard deviation of the ten calculated periods.

So we’ve got ten numbers but we had to measure ninety complete swings. Is this really an improvement?
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It would be if we had to measure the periods of ten or twenty different lengths. The ninety swings (ten measurements) are for one length, which, after calculation, gives us the uncertainty in the nine swing method of obtaining the period. For each of the other lengths, we make only one measurement of nine swings, since we already have the error in the single measurement (the standard deviation, calculated from the periods of the first length). The assumption, as stated above, is that the error in either method is independent of the time interval.

The NST is an example of how to improve the precision of an apparatus with statistical methods and is one that will be used throughout all three quarters of physics labs.

Where possible in this course we will use statistics to approximate the uncertainty of a method of measurement (which includes the physical instrument along with how it is used). We take a number of readings to establish a standard deviation and use that as the uncertainty in subsequent single readings.

**Estimated Uncertainty**

A lot of the measurements you make in the physics lab are single readings, we don't have the time or the patience to find standard deviation for each type of measurement. How do you assign an uncertainty without doing the statistics? As a start, your observation of a continuous physical parameter is limited by the resolution of your measuring device. This is known as a scale limited error. In these cases, start your estimate of the error at either $\pm \frac{1}{2}$ division or $\pm 1$ division of the device. This gives you a minimum value of the uncertainty; that is, it will be at least the scale limited error, and probably more. Among other conditions, parallax, placement of the instrument, and irregular shapes will increase the estimated uncertainty.

It is your task as an experimenter to come up with a reasonable uncertainty estimate.

**Propagation of Uncertainty**

As stated above, any calculation that uses one or more of our measurements (which have uncertainties) will itself have an uncertainty. How do we come up with a value for this error?

Starting with the algebraic expression for the calculated quantity and logically deriving the expression that is used to calculate the uncertainty is called the propagation of uncertainty. Rules and justifications for this process are contained in Appendix 2 and are summarized in the Lab References. Familiarize yourself with these rules because you are required to find your own expressions for the errors in calculated values for all experiments in the Physics Labs, starting with this one.

Suppose that an uncertain quantity $Z$ depends on $A$, $B$, and/or $C$, where $A$ and $B$ are uncertain quantities and $C$ is a constant. It is important to note that $A$ or $B$ may be calculations and not measurements. The first four rules, which you should know by heart, are as follows:

1. If $Z = C \cdot A$, then $u(Z) = C \cdot u(A)$

2. If $Z = A \pm B$, then $u(Z) = \sqrt{(u(A))^2 + (u(B))^2}$
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3. If \( Z = A \cdot B \), \( Z = \frac{A}{B} \), or \( Z = \frac{1}{A \cdot B} \), then \( u(Z) = Z \left( \frac{u(A)}{A} \right)^2 + \left( \frac{u(B)}{B} \right)^2 \)

4. If \( Z = A^n \), then \( u(Z) = |n| A^{-1} \cdot u(A) \)

You may have to apply these rules several times to get to an expression that you can calculate. As an example of propagating the uncertainty, let’s derive the one expression that you need for today’s lab.

You have to calculate the pendulum length from Eq. 2. What would be the uncertainty of this value? We start with Eq. 2 and assume that \( g \) is exact and thus a constant. Since 2 and \( \pi \) are also constants, the value \( g/(2\pi)^2 \) is then a constant. Using Rule 1 and basic algebra, we find that

\[
\begin{align*}
    u(T^2) &= u\left( g \left( \frac{T}{2\pi} \right)^2 \right) \quad \text{definition} \\
    &= u\left( \frac{g}{(2\pi)^2} \cdot T^2 \right) \quad \text{square of a fraction is the fraction of the squares} \\
    &= \frac{g}{(2\pi)^2} u(T^2) \quad \text{Rule 1}
\end{align*}
\]

We know the values of \( g \) and \( \pi \) but we don’t know \( u(T^2) \). We know that \( T^2 \) is a calculation. From Rule 4,

\[
\begin{align*}
    u(T^2) &= 2T^2 u(T) \\
        &= 2T \cdot u(T)
\end{align*}
\]

We combine Eqs. 3 and 4 to get the expression for the uncertainty in the calculated length can be written as

\[
\begin{align*}
    u(T) &= \frac{g}{(2\pi)^2} \cdot 2T u(T) \quad \text{Rule 4} \\
        &= \frac{g}{(2\pi)^2} \cdot 2T \cdot \frac{T}{T} u(T) \quad \text{multiplying by 1} \\
        &= \left( \frac{T}{2\pi} \right)^2 \cdot u(T) \quad \text{collecting terms and rearranging} \\
        &= 2T \cdot \frac{u(T)}{T} \quad \text{using definition}
\end{align*}
\]

**Equivalence of Two Values**

Theories often make exact predictions. How do we determine if our experimental measurements agree with theory? Or, as alluded to above, how can we say that the values from two different techniques agree
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with each other? At this point in today’s experiment you have two numbers, the SST and NST averages. How do you compare these two numbers to each other?

The error we associate with a measurement means that about 68% of the measurements are within one standard deviation of the average. 95% of the measurements will be within two standard deviations. This 95% level is where we draw the line for equivalency:

In this course, we use the 95% confidence level (agreement within 2σ [two sigma]) as the breakpoint for agreement.

This means that if you are comparing a measurement (e.g., 4.08 ± 0.03 J/cal) with an exact prediction (4.186 J/cal) and find that the prediction is more than two standard deviations away, you say, “My measurement of 4.08 ± 0.03 J/cal is inconsistent with the standard value of 4.186 J/cal. The discrepancy is 3%.”

If the prediction is within two standard deviations, you say, “My measurement of 4.21 ± 0.02 J/cal agrees with the predicted value of 4.186 J/cal.”

When comparing two uncertain numbers A and B to see if they agree or are consistent or are equivalent, you are really asking whether the difference of the two numbers is zero within experimental error. Using Rule 2 for propagating the error of the difference of two quantities leads to the Standard Equivalency Test (SET):

\[
|A - B| \leq 2 \cdot \sqrt{\left(\frac{u(A)}{2}\right)^2 + \left(\frac{u(B)}{2}\right)^2}
\]

Eq. 6 is the mathematical test you use to compare two numbers that are supposed to be equal. If the inequality is true, values A and B are equivalent. In practice, we input this as a logical function in Excel, explained below.

A and B are stand-ins for physical quantities. When you show an example of a SET in the Sample Calculations, do not use A and B. Use the variable names of the quantities you are comparing.

Procedure

You need the following items:

- one pendulum for the whole class
- stopwatch

The TA will give you an official data sheet. This is where you record your data and observations along with an annotated sketch of the apparatus and definitions and descriptions of what it is you are measuring, how you are measuring it, and estimated uncertainties of each type of measurement. Refer to the Lab Report Format for more details.

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Experimentally, you have to do these things:

- Record the three lengths of the TA's pendulum, based on the three hypotheses of a real world pendulum’s length.

- Measure the period of oscillation (the time of one complete swing) of this pendulum two ways:
  - 10 timings of a single swing (SST).
  - 10 timings of nine swings (NST).

Although most of the experiments in this course are designed for you to work with a partner, for this experiment you are required to take data and do the analysis by yourself.

Figure 1 Three possible definitions of the pendulum length.

1. The TA sets the length of the pendulum. There may be some confusion as to the meaning of the length used in Eqs. 1 and 2. (See Figure 1.) Allow for three different hypotheses: the length of the pendulum is the distance from the point of support to...
   a. the top of the bob,
   b. the middle line around the bob, and
   c. the bottom of the bob.

   The TA makes these three measurements along with an uncertainty estimate \( u \{ \$ \} \) and announces them for you to record on your data sheet.

2. The TA pulls the bob to the side so that the string makes an angle of no more than 10E from the vertical (a horizontal distance from the rest position that is no more than 1/6 the length of the pendulum), then lets it go.
   a. Each student measures one period with the stopwatch (the time it takes to complete a cycle back and forth). To do this:
      i. Start timing right when the pendulum changes direction (at the “top” of the swing).
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ii. Stop timing after it goes to the other side and comes back.

iii. Be sure to measure the time for a full swing. If your times are about half of everybody else’s, you’re only measuring a half period.

b. Record your times on your data sheet in a table that allows at least ten trials.

3. As the pendulum swings, make nine more measurements of the time for a complete swing, for a total of ten times. The numbers you record will differ. This is due to random errors. No one measurement is any more right or more wrong than another. Each is a statistically independent measurement of the period with an experimental uncertainty associated with it.

4. Repeat Steps 2 & 3, timing nine complete swings of the pendulum instead of a single swing. The TA keeps the pendulum swinging until everybody is finished.

   a. At the top of the swing start timing and start counting with a silent remark to yourself of, “Start!” After the bob goes to the other side and comes back, the count changes to one. Continue until you get to a count of nine.

   b. Record the time it took for the pendulum to make nine complete swings. Miscounting is a common mistake to watch out for.

Analysis
Excel has been chosen as the mandatory platform for calculations and graphs because it is ubiquitous, handles large amounts of data easily, and is adaptable to the analytical criteria of the elementary physics labs. The first two experiments are designed to introduce you to the various processes and techniques used in Excel.

Each of you will have a lab computer to work on. Some of you may have to go to an adjoining room.

- You must submit the spreadsheet file you work on in class through the In Class Analysis feature in the Meta course for your mu lab on Blackboard. You have access to this file from any computer that can get online, but it is highly recommended that you do not use Blackboard as your only form of file storage.

- Your primary storage medium should be a flash drive.

- You can store your work on the hard drive of the lab computer you are working on as long as you don’t close Excel. Be aware that files that aren’t open are deleted from all computers every half hour. It is better to work from a flash drive.

The mandatory use of Excel includes creating the layout and formatting of the spreadsheet, as well as the entering of formulas. There are times, such as with the experiment today, when much of the formatting, and occasionally the plotting, is done for you, in an Excel template. This will not be the case for every experiment, so be prepared to work with a blank spreadsheet.

Whenever you have a number on the spreadsheet or your raw data sheet, it should be clear to most people what physical quantity this number is a measure of, with the proper units. Label everything.
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Figure 2 Some of the items in a standard Excel 2010 screen.

Filling the Data Pool

1. In the lower left corner on the lab computer you are using, click on Start> Favorites> Pendulum Time Measurement Form. (Start is the Windows logo.)

   a. Type in your name.

      i. You may have to wait until other people finish because the server cannot handle the traffic.

   b. Type in the first five single swing times, numbers only.

   c. Type in the first five nine swing times, numbers only.

   d. Click on the Send Data button.

Starting Excel

2. Click Excel Templates shortcut on the Desktop then open the First Quarter folder. Double click on Measurement and Uncertainty. This starts the Excel template, which has labeled columns and cells (for data and calculations) and a chart that plots your calculated results.

   There are two separate worksheets, indicated by tabs at the bottom of the screen: Class Times and Statistics & Comparisons. You should be starting out in cell A1 of the Class Times worksheet. Figure 2 shows an annotated blank Excel 2010 worksheet with standard features. If you have used previous versions of Excel, Excel 2010 has changed a bit in the way all the features are accessed, but the features themselves are the same. You may want to go through some of the online training for Excel 2010 provided by Microsoft or access one of the many tutorials available from a search.

Transferring Data

3. Both the class data and your non-shared data need to be entered into the spreadsheet. Make sure that everybody has completed Step 1 above before you continue from here.

   a. Restore the Pendulum Time Measurement Form.
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b. Click on the Display All Data button.

c. Position the cursor just to the left of the Student Name label and click and drag all the way to the last Nine Swing time to select the class times. **Copy** (Ctrl C) this selection.

d. Switch back to Excel, make sure A1 is the active cell, and Paste the data (Ctrl V).

e. Scroll down to the last data entry. In the next line in the B column, type in your last five single swing times. Do the same for column C and the nine swing times.

   i. If you make a mistake in typing, you can select the cell and retype the entire entry which automatically deletes the contents, or you can edit it in the formula bar.

**Formulas and Calculations: Finding the NST Periods**

4. Go to cell D1. As the label T₉ (s) indicates, this column is for the NST periods, the time for nine swings divided by nine. We could use a calculator to find each of these and enter in the numbers into the appropriate cells, but it would start getting tedious after five or ten entries. Excel offers a better way.

   a. Note that in the Formula Bar, the unformatted cell content T₉ (s) is displayed and the cell reference D1 appears in the Name Box. Move one cell down to D2. Since there is nothing in the cell, the Formula Bar goes blank.

   b. Type in the equal sign from the keyboard. An equal sign appears in the Formula Bar and the last used Excel function appears in the Name Box.

   c. Click on the NST time in that row (You can also just type in C2 or c2.), type in /9 to divide by nine then hit Enter. Surprise, surprise, the Formula Bar can act like a calculator! The nine swing period is now in the cell D2.

   d. The selected cell is now D3. You could continue doing this calculation in each row, just like you would with a calculator, but, as with a calculator, it would get tedious after a few lines. The better way that Excel offers is this:

      i. Select the cell D2. A thicker line surrounds the cell and there is a tiny dark square in the bottom right corner.

         ii. Position the cursor over the tiny square. The cursor should change from a fat plus to a thin crosshair. Click and drag down column D until you have reached the same row as your last entered NST time. Release the mouse button. Yee-ha! **All** of your nine swing periods are now calculated.

**Basic Statistics**

5. Go to cell H2. As indicated, you need to calculate the average, the standard deviation, and the standard error of columns B, C, and D.
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a. Click on the equal sign by the Formula Bar. As before, the last used Excel function appears in the Name Box.

i. If the name is AVERAGE, click on it. If it is not, click on the small triangle to the right that activates a drop-down list of the most recently used functions.

ii. Click on AVERAGE if it is on the list. If it is not, click on More Functions... at the bottom. This activates the Function Wizard.

iii. A Paste Function box appears. Choose the Statistical Function category: and click on AVERAGE in the Function name: list.

iv. A box with two line windows appears; this is the formula palette for AVERAGE. These windows need to be filled out for the function to proceed. Note that Excel anticipates the numbers you want to average, suggesting the cell range B2 to G2. This isn’t what we want; we want to average the SST measurements. Two basic ways you can do this: click and drag to select all the numbers or type b2:b150 into the Number1 box. (Cell references are case-independent; Excel functions ignore blank cells.)

v. Using the Excel function STDEV in cell H3, calculate the SST standard deviation $\sigma_T$. You want the same cell range as in the previous step.

vi. In cell H4, calculate the standard error $\sigma_T$ from its definition, the standard deviation divided by the square root of the number of measurements. Use the functions SQRT (finds the square root) and COUNT (totals up all the non-blank cells in a cell range). You’ll have something like $=\text{cell reference}/\text{SQRT(COUNT(cell range))}.$

vii. Formulas for the minimum and maximum have already been entered in H5 and H6. These numbers aren’t all that important, they’re just nice to know.

b. Select cells H2:H4. As with Step 4.d.ii, go to the lower right corner of the selection, click and drag across through column J. You now have the statistics for both the NST times and NST periods.

c. Click on the Statistics & Comparisons tab to go to that worksheet. Note that the results of your calculations also appear here.

d. For ID purposes, please fill in your name and date in the appropriate cells.

Plotting a Histogram

6. We want to get a mathematical picture of the spread, or distribution, of the periods that you and everybody else in the class have measured. This picture is called a histogram. In addition to the numbers that the histogram represents, you need a list of bins, i.e., regular intervals into which the numbers fall. These bin boundaries have been calculated for you, a total of 33 slots covering your SST average $\pm 4\sigma$. This covers 99.997% of random data, but there may be people in your class who have serious systematic errors in their contributions.

a. Click on Data tab in the menu and choose Data Analysis in the Analysis group of the ribbon.
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b. Choose the Histogram Analysis Tool.

c. Indicate the cell addresses of

   i. your Input Range (all of the SST periods; you have to switch back to the Class Times worksheet to select these),

   ii. the Bin Range (cells A12:A44.),

   iii. and the Output Range (The cell where you want the upper left corner to be of a table that contains the bins and the frequencies. For the single swing, this is C11, for nine swings, E11.).

   iv. Click on OK.

d. The Bin-Frequency table appears, highlighted. Bars should appear on the histogram chart.

e. Repeat Steps a-c for the NST periods, \( T_9 \). (That’s periods, not times.)

Saving the File

7. At some point you need to save the blank template with a unique name on your flash drive or on the C: drive in the My Documents folder. Now is a good time.

   a. Click on the floppy disk icon at the top, or the File tab and choose Save As.

   b. The file type should be an Excel Workbook (file extension .xlsx) or an Excel 97-2003 Workbook (xls). If you do not have access to a computer with Excel 2010, you must save the spreadsheet as the earlier file type.

   c. Please follow these naming conventions for better file-handling:

      i. The first four characters are mua_ to designate the Measurement and Uncertainty experimental analysis.

      ii. The next letters are your Blackboard username. (Obviously, you must be registered on Blackboard. Go to http://www.blackboard.uc.edu or click on the icon on the computer desktop to do this.)

      iii. Excel will add the extension .xlsx or .xls.

   d. You should manually Save your work frequently and never close your file until you have saved it on an external storage device. Again, closed files stored on lab computers are deleted every half hour and are not recoverable.

Comparing Periods

8. Compare your two average periods using Eq.(6). (Perform the SET.)
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a. Choose the cell G6 to the right of the SET label and type in \(=\text{abs}(b4-d4)\leq 2\sqrt{\text{sumsq}(b6,d6)}\). A TRUE or FALSE will appear indicating success or failure of the test. This is the Excel formula for Eq. 6, where \(A=b4\), \(B=d4\), \(u\{A\}=b6\), and \(u\{B\}=d6\).

b. Another way is to do the following:
   i. Click on the \(\text{f}_x\) in the formula bar.
   ii. Find the absolute value function ABS and select it.
   iii. Click on the cell that contains one of the average periods, type in a minus sign, then click on the cell that has the other average.
   iv. Click in the formula bar at the end of the existing formula and type in \(\leq\). This makes it a logical formula.
   v. Now finish typing in the right side of the inequality in Eq. 6: \(2\sqrt{\text{sumsq}(b6,d6)}\). (You can type in the cell address or click on the appropriate cell as you type.)

Calculating the Pendulum Length from Period

9. Enter in the 3 lengths that were measured in Step 1 of the procedure into cells N5, N6, and N7, along with the estimated length error into N3 and the book value for \(g\) in cm/s\(^2\) into N4.

When you work with physics lab spreadsheets, follow this convention: experimental data go in shaded cells. If there is a number in a non-shaded cell, it means that it is calculated and that there is a formula in that cell.

a. Select cell N9. Using Eq. (2), calculate the length of the pendulum using the average NST period, which should have the smallest error. (What is the uncertainty of an average?) Refer to the cell where you have entered the value for \(g\) and use the Excel function, PI() for \(\pi\).

b. In cell N10, calculate the uncertainty in this calculated length from Eq. (5).

Testing Hypotheses

10. Use the SET to compare the calculated length in N9 to each of the three measured lengths in N5, N6, and N7. (Put comparison formulas in the designated cells.) Which of these three lengths, if any, is equivalent to the calculated one? If we had assumed that the length was either of the other two measurements, we would have had a systematic error.

a. Select cell O5 and type in the appropriate formula that compares the top measured length with the calculated length.

b. With appropriate use of absolute cell references, you can enter this formula once and copy it to the other two cells to do all three SET’s. The default cell reference in Excel formulas is relative. If you refer to a number in a cell two rows up and one column to the left, when you copy the formula to another cell,
that's how Excel looks for the number from that cell location. If the cell reference is absolute, no matter where you copy the formula, it always goes back to the number in that absolutely referenced cell.

i. The only number that is different in the other two SET’s is the measured length, so that cell reference has to be relative while the other three are absolute.

ii. With cell O5 selected after you have typed in the formula, double click on the calculated length cell reference in the formula bar. Hit the F4 key once to make this an absolute cell reference.

iii. Make the cell references to the two uncertainties absolute.

iv. Note that you can make the cell references absolute either as you enter in the formula or after you have entered it

c. With O5 still selected, position the cursor over the lower right corner, double click or click and drag down two rows, and release. You've just done the other two comparisons.

Submit Preliminary Analysis

You may not be able to finish all of the analysis during the allotted time. You are not expected to do so. But before the end of class you need to submit the work that you have done through the In Class Analysis page on Blackboard. A checkmark for mua should appear in your grades to acknowledge this. (It is good policy to be sure this checkmark appears before you leave class because you can’t submit a lab report unless your analysis has that check.) Your finished analysis spreadsheet must be included in your report, even though you may have finished it here.

11. Log in to Blackboard if you have not already done so.

a. Click on the Courses tab at the top.

b. From the listed Courses in which you are participating..., select the Physics 1 Lab Meta course in which you are enrolled.

c. Click on In Class Analysis> View/Complete Assignment: mua> Browse (next to Attach local file)> select the spreadsheet, Open> Submit.

d. You should soon get a message from Blackboard that the file has been successfully uploaded.

e. Save the file to your chosen form of external storage then delete any and all working files on the lab computer.

f. If there is no submitted file in your mua channel, you cannot submit a lab report.

Questions

1. Using algebra and the rules in the Lab References, propagate the error in the quantity \((T/2\pi)^2\), where the uncertainty in \(T\) is \(u\{T\}\). That is, derive the expression in the same manner as shown above for \(u\{
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\[ \varepsilon \], justifying each step. (In all Elementary Physics Labs, this is what "propagate the error" means: to explicitly show the derivation of the expression for the uncertainty in a calculated value.)

2. Three different techniques are used to measure the diameter and circumference of a circular object in order to find pi experimentally. Method A resulted in \( 3.133 \pm 0.007 \), Method B gave \( 3.1609 \pm 0.0002 \), and the result of Method C was \( 3.14 \pm 0.03 \). Which of these methods was the most accurate and which was the most precise. Why?

Remaining Tasks

You may have to finish or rework your analysis outside of class. That’s OK. But you’re by no means finished with your lab class responsibilities. In addition to doing all the spreadsheet stuff, you have to come up with a lab report that follows the Lab Report Format, in less than six days (144 hours counting from the scheduled beginning of class).

The Physics Department is introducing a new type of lab report. It is a multiple-choice assessment called a centort that is administered through WebAssign. You must complete one for this experiment. (The only other experiment that uses the centort is Momentum and Energy in 1D Collisions. The remaining six experiment require a full written Lab Report.) You are given six possibilities for each section of the Lab Report except for the Data Analysis and you choose what you think is the best one.

Assuming that you have done the experiment, have done most of the analysis, and are still in class, you have to complete the following tasks:

1. Submit the completed Data Sheet to your TA at the end of class. (You keep the colored copy.)
2. Submit an Analysis spreadsheet in the mu channel by the end of class. (This is not graded.)
3. Complete the Analysis and embed the Excel file in the Lab Report Template Word document. (Downloaded from the Lab Manual page on Bb.)
4. Fill out the ID particulars in this document.
5. Submit this document in the mu channel on the Submit Lab Report page of the Bb Meta course. (This is graded.)
6. **Do not write a full lab report!** The only section that is graded is the Data Analysis.
7. Complete the Physics 1 Centort- Measurement and Uncertainty on WebAssign.

Writing the mu Lab Report

Listed below are the steps you would have to take if you were to write the report. Because the centort is based on the report, you need to be familiar with the process. Plus, you have to write reports for other experiments. Please refer to the Lab Report Format and How to Write a Lab Report for more details.

1. Finish the Data Analysis.
2. Download the Lab Report Template. Rename it as mu__your Blackboard username__your course and section number. (This number is the first column in your grades.)
3. Embed in the appropriate place in this lab report document the final version of your analysis spreadsheet.
4. Write the Sample Calculations. The ones to include are easy to figure out for this experiment; they are $T_9$, $u\{t_1\}$, $l_1$, and one SET (not both).

   a. You have to insert them as equations, which may take some time to figure out starting from scratch. Word 2007, 2010, and 2011 are set up well for this and most computers on campus have Office 2010.

   b. If you are using your own computer, please install either Office 2010 or Office 2011 for the Mac. You can purchase this at a nominal fee from the UC Bookstore.

   c. There is a document in the Lab Manual (Equations Physics 1) that contains the starting lines of most equations you need.

   d. Copy one of the equations and paste it into your report document, making sure it is left-justified as is the following:

   $$T_9 = \frac{t_{\text{net}}}{9}$$

   e. Copy this equation and paste it two more times. If you copy it right, both copies will also be left-justified.

   $$T_9 = \frac{t_{\text{net}}}{9}$$

   f. In the second equation, substitute numbers (with units) where applicable, then in the third equation substitute the final value with units.

   $$T_9 = \frac{10.8 \text{ s}}{9}$$

   $$T_9 = 1.20 \text{ s}$$

   g. Repeat until you have samples of all five equations.

5. Do the Error Analysis.

   a. Measurement Uncertainties: This is pretty straightforward, basically indicating what quantities were measured in the experiment and the uncertainties associated with them. What was measured in this experiment? Length and time. You have to...

   i. ... describe the quantity and how it was measured.
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ii. ... give the numerical value of the uncertainty. Keep it to 1 significant figure! (2 s.f. if the mantissa of the number expressed in scientific notation is between 1 and 2. E.g., u{x} = 0.0346 m should be stated as 0.03 m; u{m} = 1.5739 g should be stated as 1.6 g.)

iii. ... state how the number was found.

Note that this uncertainty generally is the same number that you recorded on the data sheet. The exception is if the uncertainty were found statistically, as is the case in this experiment with the time t. In this case, u{t} is the standard deviation of one of the time measurements, not the scale-limited error.

b. Systematic Errors: This confuses everybody. A systematic error is what happens when the theory does not take everything into account that may have affected the measurements. It can be from an oversimplified theory or from an incorrect measurement done consistently. Sometimes these errors are obvious, sometimes not. If you cannot identify any systematic errors, you state, “No systematic errors were identified.” You might be wrong, but that’s what you say. Anytime you state a systematic error, you must also state how it affected your results. (Results are the results of the analysis, not the measured data.)

c. Propagated Uncertainties: These are errors in calculated values, a number usually calculated from an expression found through the propagation of uncertainty process. You are just stating values here (to 1 or 2 s.f.), you are not showing derivations or calculations. If this number was found from an Excel function like STDEV, you state that fact. For this experiment, you state two values, u{T\over 2\pi}^2 and u{l} (this is for the calculated length, not the measurement).

5. Write the Theory and Concepts. Be careful. The premise in this experiment is not the same as the purpose. Independent of the new techniques and procedures being introduced (which can be overwhelming), you are testing two physical ideas:

a. ... that measurements of a physical quantity should give the same result regardless of the technique.

b. ... that the length of a pendulum calculated using the experimental period should tell us how to measure the length.

6. Write your Experimental Results and Conclusions.

a. How did the two averages compare?

b. Which of the three hypotheses is correct?

7. Answer the Questions. Note that for Question 1, the steps you take to derive u{T\over 2\pi}^2 are similar to that for u{l}, but they are not the same.

8. Write the Abstract. This is short and sweet. Again you are reporting on the experiment, not the exercise.
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9. Save your file as a Word document. It should have a docx or doc extension.

10. Upload the file to Blackboard (Save) in the mu channel on the Submit Lab Report page from the Meta course menu. If this channel doesn’t appear, you haven’t passed the Academic Misconduct Test at 100% or you haven’t submitted a spreadsheet in the mua channel.

11. Double check that the file that is on Blackboard is the one you want graded, (It may be different than the file on your computer.) then Submit.

After you submit any lab report, always open the uploaded file that is on Bb using a different computer than the one on which you created the report, specifically a PC running Office 2010. Both the Word file and the embedded Excel spreadsheet should open without any problems, be readable, and be what you want graded.

Data Graphics and Analysis (last edited December 29, 2011)

Dr. Larry Bortner

Learning Objectives

Estimate measurement uncertainties.

Plot a set of points with error bars on a scatter plot in Excel.

Perform a linear least squares fit on a set of points to find the slope and y-intercept (and their uncertainties) of the best line through these points.

Purpose

To plot a data set that is theoretically linear, to use a least squares fit to find the best possible line through these points, and to find the acceleration of gravity.

Background

The Pendulum

Recall from the previous experiment that, for small swings, the period T of a pendulum of length \( l \) is given by

\[
T = 2\pi \sqrt{\frac{l}{g}},
\]

(1)
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where the acceleration of gravity is \( g = 9.80 \text{ m/sec}^2 \). Expressing the length as a function of the period gives

\[
\ell = g \left( \frac{T}{2\pi} \right)^2
\]

(2)

The goal of this experiment is to verify Eq. 2. To do this you measure the periods of a pendulum of different lengths then analyze the data to find the acceleration of gravity. Examine Eq. 2 and recall that the equation of a line is \( y = mx + b \). If Eq. 2 is correct, when you measure various pendulum lengths and their corresponding periods and plot \( \ell \) vs. \( (T/2\pi)^2 \) (length along the y-axis and the period over two pi squared along the x-axis), you should get a straight line with slope equal to \( g \) and with a y-intercept of zero.

**Least Squares Fit**

How do you find the slope from a typical set of paired data, assuming that the x- and y-values are linearly related? If you don’t have a computer or a calculator, the process of doing it by hand goes something like this:

- Get a sheet of graph paper.
- Determine the scale on each axis from the range of x- and y-values.
- Title the graph and label the axes.
- Plot each point.
- Draw the best line through the points using a ruler and your eyeball.
- Then pick two points (at opposite ends) off this line to calculate the slope.
- Assign an error to the slope through graphical techniques. One way is to draw the two “worst” lines through the points, find their slopes, and see how they deviate from the best line slope.

This method works, it has worked for hundreds of years. But it is time-consuming, subjective, and inherently imprecise. Mind you, it is certainly worthwhile to plot an occasional data set by hand, just like it is worthwhile to get up and stroll around the block or hike through the woods instead of driving a car or riding a dirt bike. But if you want to get to Seattle or London from Cincinnati, a form of transport different from walking is recommended, just as you want to use a computer to analyze large or precise data sets instead of sweating and cursing over papers and pencils and rulers (and yes, even calculators).

A better way to find the slope and y-intercept of a set of two variables that are supposedly proportional is numerical in nature and is called the *method of least squares*. (See Appendix 3.) This process is also called a *linear regression*. It is straightforward though involved, and can be programmed on a calculator or computer. Your calculator may already have a function that does most of this automatically. Excel has a least squares fit function for lines called LINEST that we use to analyze possible linear data sets.

**Procedure**

You need the following items:

- adjustable length pendulum with stand
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- tape measure
- computer with Science Workshop interface
- photogate

1. Click on Data Studio Experiments> First Quarter> Pendulum.

2. For the first length, set the distance from the line in the middle of the cylinder to the string attachment point to be about 30 cm. Measure and record this distance in your data table, as well as your estimated uncertainty in that distance. The connection of the pendulum string at the top is by a compression fit. You do not need to tie the loose end of the string to anything.

To reiterate: Any type of measurement has some uncertainty. It is the responsibility of the experimenter (you) to determine this uncertainty. Often this is done with an estimate, starting off with the scale-limited error then adding some padding. Always record an initial estimate, even if statistical analysis is used for a more realistic value.

Figure 1 Measuring the pendulum period with a photogate.

**Estimating Uncertainty**

To make your estimate, start with the scale-limited error, or resolution, of the instrument (0.5 − 1 mm for a metric tape) and go up from there. The thing to think about is that if somebody else came in and measured the same quantity with the same apparatus, would they come up with your number? If not, how close would they come?

3. Adjust the support on the stand so that the pendulum bob rests between the arms of the photogate but can swing freely. (See Fig. 1.) For the timing program to work, the beam between the photogate infrared source and the sensor has to be interrupted.

**Measure the period**

4. Start the pendulum swinging so that it doesn’t crash into the photogate. The angular displacement should be less than 10°. (Eq. 2 is valid only for “small” swings.)

a. Click on the Start button in the upper left corner of the window. A number should appear in the digital readout.
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1. Keep this timer running until you’ve measured periods of all the lengths. I.e., do not press Stop until Step 7.

   b. This number is the period for each complete swing. Record this period after a couple of swings. Assume that the uncertainty you associate with measuring the period this way is the scale limited error of 0.001 seconds.

5. Increase the length by about 10 cm.

   a. Slide the pendulum support up the stand about 10 cm.
   b. Unscrew the string stop and let out about 10 cm of string.
   c. Record the actual distance from the support to the middle of the bob.
   d. Measure the period as in the previous step.

6. Repeat step 5 until the distance is at least 80 cm, then repeat Step 5 increasing the length by 20 cm instead of 10 cm, up to at least 160 cm.

   a. This gives you a minimum of 10 data pairs of distance and time. (It’s OK to take more.) At about 80 cm (maybe longer) you’ll have to swing the pendulum over the edge of the lab bench (set the photogate on the floor).
   b. You must measure the period of the pendulum for the following approximate lengths in cm: 30, 40, 50, 60, 70, 80, 100, 120, 140, 160. (Your lengths do not have to be these numbers exactly but you must set, measure, and record each length to the nearest tenth centimeter.

7. Click on the Stop button to stop the timer. Keep the DataStudio program running until the end of class, just in case you have to retake data.

Analysis

Although you worked with a partner to gather the data, this is another experiment where you must do all the computer analysis by yourself. After finishing the Procedure, one of you will go to another computer.

One trick you may already know about both Excel and Word is the Undo function; \(^Z\) or the sweeping counterclockwise arrow at the upper left. It reverses the previous action, usually applied after typing or deleting the wrong thing. There is also a Redo action (\(^Y\) or clockwise arrow) that undoes the Undo.

1. To open a spreadsheet based on the Excel template for today's experiment, click on Excel Templates> First Quarter> Data Graphics and Analysis.

Labels and Cell Formatting

Whenever you have a number on the spreadsheet or your raw data sheet, it should be clear to most people what physical quantity this number is a measure of, with the proper units. Label everything clearly.
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The origin of each number in your spreadsheet should also be apparent if it’s not raw data, it’s a calculated quantity. Some of the cells are shaded a light blue. This is where you will be entering your data. As mentioned in the first experiment, this shading is to distinguish observed values from calculated values (that is, from Excel formulas). When you create your own spreadsheets for analysis, follow this convention: Raw data are in shaded cells.

2. Select cell C1, type in \( u_T \) (s), and hit Enter. This takes you to cell C2.

   a. Type in \( u_l \) (m). (That's a lower case “L.”)

   b. To remove ambiguity, you want to make the small ell a script ell.

      i. Select the l, either in C2 or in the formula bar. You want to change the font of this single letter, not the whole cell.

      ii. Once you make the selection, a faint toolbar appears above and to the right. The closer you hover the mouse cursor to this, the more opaque it becomes.

      iii. This toolbar contains an abbreviated selection of the buttons contained in the Font group of the Home tab in the Ribbon.

      iv. Right-clicking the mouse makes the toolbar opaque and also presents a pop-up editing menu.

      v. In any case, the Font box reads Times New Roman or some abbreviated version thereof. Click on the drop down arrow at the right of the Font box to bring up the list of installed fonts.

      vi. Type sc. This should take you directly to the Script font. Select this font to change the length abbreviation to a script l.

**Greek letters**

3. We want 2 pi in cell C3, but we want the pi symbol, not the number. Type 2 into C3.

   a. Click on the Insert tab and choose Symbol in the Text group (with an icon of a capital omega, \( \Omega \)) to bring up the Symbol table.

   b. The Font: should be Times New Roman or Cambria and the Subset: needs to be Greek and Coptic or Basic Greek. Alternatively, you can scroll down through the character set until you find the Greek letters. If the Greek letter pi is already listed in the Recently used symbols:, you don't have to do any searching.

   c. Double click on the \( \pi \) letter or click on Insert with \( \pi \) selected, then close the table.

**Superscripts and Subscripts**

4. In cell C5 type in \((T/2)^2\) (s²). We want this label to read \((T/2\pi)^2\) (s²).

For labels, the units of a quantity are placed in parentheses at the end.
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a. Highlight the second of the three 2’s, either in the cell or in the formula bar. We want to superscript this to indicate squaring.

b. Right click and select Format Cells... from the pop-up menu.

c. In the Effects box for the Font, check Superscript.

d. Insert a π between the first 2 and the first closing parenthesis.

e. Select the 2π and Subscript it (similar to the procedure for Superscripting).

f. Superscript the two remaining 2's to indicate squaring.

5. In D5 type in l (m). (Again, that's a lower case “L.”) Make it a script l.

There are other ways to create labels in Excel that contain algebraic expressions. This way is the most straightforward. You can create an equation in Word (“Alt + =”), then copy and paste it into the appropriate cell or you can insert a Microsoft Equation 3.0 Object.

Copying a cell

6. F5 is to contain the label of the uncertainty of \((T/2\pi)^2\), \(u\{(T/2\pi)^2\}\) (s2). We could just repeat most of what we did in Step 4. Or we could make use of the work we’ve already done. Copy cell C5 into cell F5. There are several ways to do this with keyboard or mouse commands. The quickest way to do this is as follows.

a. Select cell C5.

b. Position the cursor on the border of the selection (as long as it's not the lower right corner). The cursor changes from a fat plus to an arrow.

c. While pressing the Ctrl key, click and drag to cell F5.

7. Click in the formula bar before the opening parentheses.

a. Type in \(u\{\).

b. Move the blinking cursor in the formula bar to right after the 2 that indicates the square of T/2π and type in the closing brace, \}.

c. You don’t want the closing brace to be superscripted, so select it> right click> Format Cells...> uncheck the Superscript box.

8. The remaining cell labels have been filled in for you.

Data

9. Enter into the appropriate cells: 155
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a. ... the values of \( u(T) \) and \( u(l) \),

b. ... the paired periods and lengths.

**Calculations**

10. In D3, enter in the formula =2*pi(). (The Excel function pi() calculates \( \pi \) to 15 decimal places.)

11. Enter in the appropriate formula for \( (T/2\pi)^2 \) in C6 and for \( u((T/2\pi)^2) \) in F6, using relative and absolute cell references. (You have found the expression for \( u((T/2\pi)^2) \) from the Question in the previous lab. Double check with your TA to make sure it is the correct expression.)

12. Copy the formulas as needed to complete the table.

**Plotting**

As stated in the *Lab Report Format*, the following pertains to all of your plots, which must be created and presented in Excel:

- The plot must have a descriptive title.
- The axes must be clearly labeled with the correct quantities and units.
- The best curve that fits the points must be drawn through them.
- The points must have error bars.

Except for the first experiment's histogram, all of the plots you generate in basic physics labs are referred to in Excel as the XY scatter type.

13. To draw a plot (or Chart in Excel terminology) of the data, the first thing to do is to highlight (select) the x- and y-values in columns. As alluded to in the Background discussion, \( (T/2\pi)^2 \) is the x-coordinate and \( u \) is the y-coordinate. Click on the first \( (T/2\pi)^2 \) value in C6, hold the mouse button down, and drag the cursor to the last \( u \) value.

The graphing or plotting of a data set is always \( y \) vs. \( x \).

a. Click on the Insert tab in the ribbon.

b. From the Charts group, select Scatter then Scatter with only Markers. A plot of your data is created and the contextual Chart Tools Tabs (the Design, Layout, and Format tabs) are added to the ribbon. These tabs are only visible when the chart is active, i.e., when the chart is selected.

c. The Design tab is automatically selected. From the Chart Layouts group choose Layout 9. This automatically inserts a default plot title and default axes titles and draws the best line through the points.
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d. Delete Chart Title and insert your own. The graph title should indicate what the graph is trying to represent. The generic y-variable vs. x-variable is a step up from Chart Title but something more descriptive is preferred. You want to communicate, to inform. For instance, Motion of a Freely Falling Body imparts more information than v vs. t. Give the title some context. For this particular graph, Finding \( g: T^2 \text{ Relation To Pendulum Length} \) is more informative (and less boring) than \( \theta \text{ vs. } (T/2\pi)^2 \).

e. Change the vertical Axis Title to indicate the pendulum length, with units in parentheses.

f. Similarly, for the horizontal Axis Title, state the variable name, with units.

g. From the Layout tab, choose Labels> Legend> None. Since you’re only plotting one data set, you don’t need a label on the side of the graph saying that this is your first data series. There are other experiments in this course where you definitely want a legend because there is more than one data set. When there is a single data set, do not include a legend.

**Positioning and Sizing the Graph**

14. Position the cursor on or just inside the border of the chart box. It changes from a fat plus to crossed, double-headed arrows. Click and drag the graph so that its upper left corner is in cell A21.

a. Place the cursor over the lower right corner of the box. It takes the shape of a diagonal double-headed arrow. Click and drag to cell K50.

b. As long as the chart is selected, when you position the tip of the arrow cursor on a point in the graph, a small informational window identifying the point pops up. Do this for one of your points, just to check it out.

c. This should be an accurate experiment, with all of your points falling on the same line. If there are one or more points that are far away from the included line, do the following:

i. Double check your data sheet to make sure that the numbers were typed in properly.

ii. Retake the data for any bad points.

**The Best Line**

15. The linear Trendline that Excel has drawn through your points gives the slope and y–intercept, as well as the R2 value. A value of 1 means that all of the points fit on the line, while a value of 0 means that there is no linear correlation between the two quantities.

**Least Squares Fit with Errors**

16. Although the Trendline gives you the slope and the y-intercept, to better state your experimental findings, you also need the errors associated with these calculated values. The Excel function that finds all four of these values is called LINEST (for LINe ESTimation). The way we typically use this function, four numbers will be returned in a 2 x 2 cell array. The slope of the best line will be in the upper left, the y-intercept in the upper right, the error in the slope in the lower left, and the uncertainty in the y-intercept...
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in the lower right. Note how these values are labeled, because you will have to do this on your own in future experiments.

a. Select the four-cell rectangle of C18, D18, C19 and D19 (In Excel terminology, this is C18:D19.). Lines have been drawn around these cells.

b. Click on the f_x sign and find the LINEST function, as you did for AVERAGE or STDEV in the first experiment.

c. A box with four line windows appears; this is the formula palette for LINEST. These windows need to be filled out for the least squares fit to proceed. Move this box to the right side of the screen by clicking and dragging. The data that you just typed in should be visible.

d. A vertical blinking line cursor should appear in the Known_y’s line. Highlight the pendulum lengths. A moving dotted line appears around your selection. The formula palette reduces to a single line while you are dragging.

e. Click in the Known_x’s line in the formula palette. Repeat the previous step for the \((T / 2\pi)^2\) values.

f. Click in the Const window. Type in 1. This instructs the function to calculate the y-intercept normally and not force it to be zero.

g. Click in the Stats window. Again, type in 1. This logical flag tells the function to calculate the statistical errors of the slope and the y-intercept.

h. Holding down Shift and Ctrl keys at the same time, hit Enter. The slope and the y-intercept are now in the first row of the highlighted box, with their corresponding errors in the second.

i. Click on the Decrease Decimal icon in the formatting toolbar (See Figs. 2 & 3.). Continue clicking on this until one or both of the errors are reduced to one significant figure. You may need to highlight just the slope and its error and reduce the decimal places because the two errors have different precisions.

Figure 2 The Decrease Decimal toolbar icon in Excel 2003.

Figure 3 The Decrease Decimal icon in Excel 2007.
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Significant figures: When reporting a value that has an error or uncertainty associated with it, reduce the error to one significant figure (two if it’s between 10 and 20). This determines the decimal place of the value to report.

Adding Error Bars

17. In most graphs there will be some fuzziness in one or both of the x- and y-coordinates of each point. You indicate this on the graph with error bars.

a. With the chart selected, choose Error Bars from the Analysis group of the Layout tab, then More Error Bars Options… This brings up the Format Error Bars window with the Vertical Error Bars selected.

b. In the Display box choose Both for the Direction and Cap for the End Style.

c. Set the Fixed value: of the Error amount to your estimated value of $u\{\ell\}$.

d. Click on one of those huge horizontal error bars or change the Current Selection in the Layout tab to Series 1 X Error Bars. The uncertainty of the length is constant and independent of the value, but as you can see from your last calculated column, $u\{(T/2\pi)^2\}$ changes. We have to tell Excel which error goes with which point.

e. Click the Custom: radio button then the Specify Value button. A Custom Error Bars window pops up.

f. Click in the Positive Error Value window then click and drag the cells in the spreadsheet to select all calculated values of $u\{(T/2\pi)^2\}$. When you do this the Custom Error Bars box minimizes and a moving dotted line appears around your selection. When you release the mouse button, the box returns to size.

g. Repeat Step f for the Negative Error Value.

h. When you deselect the plot, the points should appear with error bars. Of course, since you are such an excellent experimenter, you may not be able to see them because your measurements are so precise that the errors are too small to show up. Generally the errors have to be at least a half percent of the maximum of the corresponding axis to be easily visible, which may not be the case today. But you still have to add error bars whenever you do a plot. Just be sure to mention in the Conclusions section of your report that they're too small to show up if that's the case.

18. Compare the slope from Step 15 with the accepted value of $g = 9.80 \text{ m/s}^2$. (Surely you haven’t forgotten how to compare two numbers, as you did in the Measurement and Uncertainty experiment?)

Questions

1. Two students doing this experiment came up with a slope for $\ell$ vs. $(T/2\pi)^2$ of $9.86 \pm 0.04 \text{ m/s}^2$. How does this compare with the value it should be? (Are the two values equivalent?) Why?

2. Propagate the uncertainty of $v = \frac{\Delta x}{\ell}$, where $x$ and $t$ are measured values.
Falling Bodies (last edited December 29, 2011)

Dr. Larry Bortner

**Learning Objectives**

Explain the parabolic time dependence of the distance a mass moves under constant acceleration, as well as the linear time dependence of its velocity.

Create an analysis spreadsheet from a blank Excel sheet.

**Purpose**

To investigate the motion of a body under constant acceleration, specifically the motion of a mass falling freely to Earth. To verify the parabolic time dependence of the distance fallen and the linear time dependence of the velocity.

**Background**

We use a digital free fall apparatus to measure times that a mass falls a given distance. This apparatus consists of a launcher with a screw release, a large ball bearing, a touch sensitive landing pad, and a millisecond-resolution digital timer operated through the Science Workshop interface (Fig. 1).

![Figure 1 Digital free fall apparatus.](image)

The experiment consists of measuring the distance from the ball in the launcher to the landing pad, then timing the ball dropping this distance. As noted in the Measurement and Uncertainty experiment, there will be some randomness associated with measurement of the time. The experimental fall time varies.
Reforming the intro physics lab to impact SR

because of non-uniformity of both the release method and the initial ball position. Thus we need to determine $u(t)$ statistically.

This data gives you the distance $x$ vs. time $t$ curve. For a constant acceleration $a$, zero initial position and zero initial velocity, one of the equations of motion is

$$x = \frac{1}{2}at^2$$

From basic algebra (Oh, no!) we know that this is a quadratic equation and that when we plot it, the resulting curve is a parabola.

There are two different ways to express the average velocity of the ball after it falls a certain distance from rest:

- One way is to take the average of the initial velocity $v_0$ and the final velocity $v$. The ball isn’t moving when we first release it, so $v_0$ is zero. Without friction, $v$ is also the instantaneous velocity of any object that has fallen the same distance starting at a zero initial velocity. Then $v_{av} = (0+v)/2 = v/2$.

- The other way is to divide the distance traveled by the time it took: $v_{av} = x/t$.

Equating the two, we get that

$$v = \frac{2x}{t}.$$ 

A second equation of motion of an object under a constant acceleration $a$ is

$$v = v_0 + at.$$ 

So if we calculate the velocity from Eq. 2 and plot it against the corresponding time, we should get a straight line with a slope equal to the acceleration of gravity $g$, and a zero $y$-intercept (the ball is falling from rest).

A note to clarify matters:

We seek to experimentally verify the equations of motion under constant acceleration, specifically Eqs. 1 and 3. Note that there are two different expressions for the velocity of the falling ball. One of the expressions, Eq. 2, is derived independently of the equations of motion under a constant acceleration. We use Eq. 2 to calculate the experimental value of $v$. Eq. 3 and Eq. 1 come from the theoretical mathematical model that we are trying to prove.

How do you calculate the velocity in the Analysis? **You have to use Eq. 2.** If you use Eq. 3, you are using the equation to prove the equation; that is, you get perfect results but you don't prove anything. This is something you have to watch out for in any experimental endeavor. Be aware of the context of any equation given in the Background.

**Procedure**
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You need the following items:

- meter stick and 2-meter stick
- launcher with set screw release
- ball bearing
- landing pad
- Science Workshop interface
- computer

1. Set up the following two tables on your data sheet:

<table>
<thead>
<tr>
<th>for x=</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>u{x} (cm)=</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trial #</th>
<th>t (s)</th>
</tr>
</thead>
</table>

and

<table>
<thead>
<tr>
<th>x_{suggested} (cm)</th>
<th>x_{actual} (cm)</th>
<th>t (s)</th>
</tr>
</thead>
</table>

2. Click on Data Studio Experiments> First Quarter> Falling Bodies to start the DataStudio program.

3. Set the ball in the release mechanism.
   a. Push in the pin at the top so that the ball is nestled in the hole of the flexible metal strip, between the brass contact and the strip. (See Fig. 2.)

![Figure 2 Putting the ball in the launcher.](image)

b. Lightly tighten the thumb screw to lock the ball in place. Make sure the landing pad is directly beneath the ball.

4. Set the initial distance that the ball falls to between 5 and 10 cm, measuring from the landing pad to the bottom of the ball with a meter stick as in Fig. 3.
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a. Record the actual distance in cm.

b. Record your estimate of the uncertainty of the measurement, \( u_x \). How dependent is your measurement on the viewing angle? When or where exactly does the ball bearing cause the circuit to be completed and the timing to stop?

Figure 3 Measuring the ball drop distance.

5. Click on the Start icon at the top of the DataStudio window.

6. Untwist the thumb screw to release the ball.

7. Record the Time of Fall.

   a. If the ball did not land on the pad, disregard this time (a single line through the number) and retake the data.

   b. Do not click on the STOP icon.

   c. Reseat the ball.

8. Repeat Steps 6 and 7 until you have ten valid times.

   • The timer automatically resets when you untwist the set screw after locking the ball.

   • There should not be a spread of more than 0.010 s.

One of the many things to learn from the Measurement and Uncertainty experiment is that…

The standard deviation of any ten measurements of a single quantity measured in the same way is the uncertainty in any single measurement.

We assume that this error in the time measurement is independent of the time interval, meaning that it will be the uncertainty in the times measured at all distances. So your time uncertainty \( u_t \) for this experiment for each timing is the standard deviation of these ten times. You still estimate an uncertainty of the time to record on your data sheet, but do not put any calculations on the data sheet. In the Error Analysis of your report, you state the calculated standard deviation as the actual time uncertainty.
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9. Make single time measurements for each of the suggested distances in the following table. They do not have to be exact. As long as you're within a few millimeters, you're OK.

a. For the last distance, make it as large as you can_ put the landing pad on the floor and position the launcher as high as it will go and so that the ball will drop over the edge of the lab bench. Use the two-meter stick to measure the distance.

b. After the measurements you should have at least 30 times; 10 times for the first distance and single times for the 20 subsequent distances.

<table>
<thead>
<tr>
<th>x (cm)</th>
<th>x (cm)</th>
<th>x (cm)</th>
<th>x (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.6</td>
<td>33.1</td>
<td>47.1</td>
<td>63.5</td>
</tr>
<tr>
<td>23.7</td>
<td>35.7</td>
<td>50.2</td>
<td>67.1</td>
</tr>
<tr>
<td>25.9</td>
<td>38.4</td>
<td>53.4</td>
<td>70.8</td>
</tr>
<tr>
<td>28.2</td>
<td>41.2</td>
<td>56.6</td>
<td>74.5</td>
</tr>
<tr>
<td>30.6</td>
<td>44.1</td>
<td>60 (to the floor)</td>
<td></td>
</tr>
</tbody>
</table>

10. Click on the timer Stop button and exit DataStudio. Do not save the activity.

Analysis

1. There is no template for this experiment. Starting from the Excel Template> generic lab spreadsheet, copy in your first distance, the uncertainty \( u_x \), and the ten times in appropriately labeled cells. Remember to label the cells appropriately and to shade all data cells.

2. Use the AVERAGE function of Excel to calculate \( t_{av} \) for this distance.

3. Use the STDEV function to calculate \( u_t \).

4. Type these headings into your spreadsheet:

<table>
<thead>
<tr>
<th>t (s)</th>
<th>x (cm)</th>
<th>v (m/s)</th>
<th>( u_v ) (m/s)</th>
</tr>
</thead>
</table>

5. Fill in the first two columns with your distance and time data. In the first row, the first time should be \( t_{av} \) and the first distance the initial distance where you took the ten times.

6. In the third column calculate the instantaneous velocity \( v \) in meters per second from Eq. 2. Note that this calculation includes a units conversion.

7. In the fourth column, calculate the propagated error \( u_v \) in the velocity from the following expression:
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\[ u(y) = y \sqrt{\left( \frac{u(x)}{x} \right)^2 + \left( \frac{u(t)}{t} \right)^2} \]

(4)

8. Plot \( x \) vs. \( t \). The distance \( x \) is along the y-axis and \( t \) is along the x-axis.

a. Highlight the two columns of data values for \( t \) and \( x \).

b. From the Insert tab in the Charts group choose Scatter> Scatter with only Markers.

c. From the Design tab of the Chart Tools in the Chart Layouts group, choose Layout 9. This layout automatically inserts text boxes for the chart and axes titles, as well as a linear trendline.

d. Move the graph to the top of the spreadsheet and resize it, making it bigger and squarer.

e. Remove the legend and give appropriate titles to the chart and axes.

f. The line seems to fit the middle points OK, the endpoints not so much. Recall that our theoretical relationship between \( x \) and \( t \) (Eq. 1) tells us that these points should fall on a parabola. Let’s see if this is the case. Right click on the trendline and choose Format Trendline… from the popup menu.

g. In the Trendline Options choose a Polynomial of Order 2 for the Trend/Regression Type, Forecast Backward 0.2 periods, and Display Equation on chart. (Display R-squared value on chart should be unchecked.)

h. The \( x^2 \) coefficient in the equation should be close to \( \frac{1}{2}g, 490 \text{ cm/s}^2 \). How well do the points fit the parabola? Does the bottom of the parabola cup coincide with the origin?

i. Include x- and y- error bars.

9. Plot \( v \) vs. \( t \) with a linear trendline.

a. Highlight the \( t \)-values. While holding down the Ctrl key, highlight the corresponding \( v \)-values.

b. Click on Insert> Charts> Scatter> Scatter with only Markers.

c. Click on Chart Tools> Design> Chart Layouts> Layout 9.

d. Move the graph below the first and resize it so that they are about the same size.

e. Right click on the trendline and Forecast Backward 0.2 periods. (Display R-squared value on chart should be unchecked.)

f. Include x- and y-error bars. Chart Tools> Layout> Analysis> Error Bars> More Error Bars Options…
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i. For the Vertical Error Bars, you have calculated a different \( u(v) \) for each \( v \), so you have to enter all of these as Custom> Specify Value, for both the Positive Error Value and the Negative Error Value.

ii. From Chart Tools> Layout> Current Selection, change Series 1 Y Error Bars to Series 1 X Error Bars. \( u(t) \) is the same for all values of \( t \), so this is a Fixed value.

10. Do a least squares fit with errors of \( v \) vs. \( t \) (i.e., use LINEST to get the slope, y-intercept and errors in the slope and the y-intercept).

   g. Compare the slope with the accepted value of 9.80 m/s\(^2\) and the y-intercept with the expected value.

Questions

1. In Step 4 of the Procedure, why don’t we measure the distance to the center of the steel ball instead of to the bottom?

2. Is the diver below correct in his calculation? If he steps off that board, how fast in miles per hour would he be going when he hits the water? Show your work.

   Is this guy really a whiz?

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Vector Forces (last edited December 29, 2011)

Dr. Larry Bortner

Learning Objectives

Demonstrate the principles of static equilibrium by adding force vectors of weights balanced in two dimensions.
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Add two vectors graphically with a triangle, protractor, straight edge, and compass.

Draw arrows on an Excel plot.

**Purpose**

To experimentally verify the vector laws of addition. To demonstrate that a system in equilibrium has no net force on it (i.e., the vector sum of the forces must be zero).

**Background**

A two-dimensional vector is a mathematical quantity that needs two numbers to define it unambiguously. This is analogous to locating a point in a plane, where the tail of the vector is at the origin and the pointed head is at the point (see Figure 1).

![Figure 1 2D displacement vector.](image)

**Vector Representation**

Typically for vectors the two numbers are a magnitude and a direction. For a displacement vector from the origin, this is the length \( r \) in the example below and the angle \( \theta \) measured counter clockwise from the x-axis. This is equivalent to giving the polar coordinates of the point at the head of the vector. We’re probably all more familiar with giving the xy or Cartesian coordinates of a point and we can define a vector similarly. We give the x- and y-components. These are the lengths of a vector along the x-axis and one along the y-axis, the vector sum of which is the original vector. As pictured, the sum of these two right-angled vectors is the diagonal across the rectangular box suggested by the two components. Finding the magnitudes of these two vectors is called *breaking a vector down into components*.

For a displacement vector you can look at the vector representation as a set of directions to go from the origin to a particular point. The Cartesian description tells you to go a certain distance due east (or west), then turn and go another distance due north (or south). Polar coordinates tell you to go a certain distance in a particular direction. With both sets of direction you end up at the same location.

For a vector \( \vec{F} \) at an angle \( \theta \) measured in the counterclockwise direction from the positive x-axis that has x- and y-components x and y, the transformations between the two descriptions is
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Vector Rules

If you are adding a bunch of vectors, the analytical technique is to

1. Break all the vectors down into components.
2. Add all the x-components as straight numbers.
3. Add all the y-components similarly.
4. Convert back to the magnitude and direction description to state the final single vector.

Two vectors are equal if and only if they have the same magnitude and direction or, equivalently, if both the x-components are equal and the y-components are equal. Note that equal vectors do not have to occupy the same space. This means that as long as we keep the same orientation, we can put a vector anywhere we want it.

Vector Forces

According to Newton's second law of motion, a body undergoes an acceleration that is directly proportional to the net force exerted on it. Since both these quantities are vectors, this means that the net force and acceleration are in the same direction and their magnitudes are directly proportional to each other. In static equilibrium, a body is not moving. Obviously, then, the acceleration is zero and from Newton's second law the net force must also be zero.

In this experiment, we apply forces to an object so that it is in an equilibrium condition, then measure the vector forces and sum them to see if they do indeed add to zero.

The apparatus used in this experiment is called a *force table* (Figure 2). The table consists of a circular top supported by a heavy tripod base. There is a small peg located at the center of the top and the perimeter of the table is graduated in degrees. Forces are applied to a small ring by means of strings connected over pulleys to weight hangers. By varying the total mass on each string as well as the direction at which each string acts, one can adjust the equilibrium position of the ring so that its center is the peg. This equilibrium configuration is the only one where the angles measured along the edge signify the correct direction of each string.
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Figure 2 The force table.

There will be four strings and pulleys in the present system (see Figure 2; the fourth string is not used here but you will be using it). The vertical tension in each string is equal and opposite to the weight of the supported mass. Each pulley redirects this tension onto the ring. Therefore the net force acting on the ring can be written as

\[ \mathbf{F} = \sum_{n=1}^{4} \mathbf{F}_n = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 + \mathbf{F}_4 = 0 \]  

(2)

The vector sum has been set equal to zero because the acceleration of the ring is zero, as mentioned above. If all of the strings lie in a common plane, we can treat the forces in Eq. 2 as two dimensional vectors.

With the force table:

- The origin is at the center where the peg is.
- The positive x-axis is a ray starting at the peg and containing the $\theta = 0^\circ$ mark.
- The positive y-axis is along a ray from the center through the $\theta = 90^\circ$ mark.

Breaking the individual vectors into components, we rewrite Eq. 2 as:

\[ \mathbf{F} = \sum_{n=1}^{4} \left[ (f_n \cos \theta_n) \mathbf{i} + (f_n \sin \theta_n) \mathbf{j} \right] \]

\[ = F_x \mathbf{i} + F_y \mathbf{j} = 0 \]

(3)

where $F_n = |\mathbf{F}_n|$, $\theta_n$ is the counterclockwise angle between $\mathbf{F}_n$ and the x-axis, and $\mathbf{i}$ and $\mathbf{j}$ are the unit vectors along the x- and y-directions, respectively. Note that for a vector to be zero, all of its components have to be zero. This leads us to the set of equations.
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\[
\begin{align*}
F_x &= f_1 \cos \theta_1 + f_2 \cos \theta_2 + f_3 \cos \theta_3 + f_4 \cos \theta_4 = 0 \\
F_y &= f_1 \sin \theta_1 + f_2 \sin \theta_2 + f_3 \sin \theta_3 + f_4 \sin \theta_4 = 0
\end{align*}
\]

These equations can be checked experimentally by setting up four arbitrary weights at arbitrary angles on the force table, as long as the ring is centered. The four angles are measured by the angular position of the pulleys. The magnitudes of the four vector forces acting on the ring are just the total weights hanging from the strings. Since gravity is constant to many significant figures in the lab, we’ll just use force units of gram weights, where the acceleration of gravity \(g=1\):

\[
f_n = m_n
\]

where \(m_n\) is the \(n^{th}\) mass.

The method of evaluating \(\vec{F}\) by calculating \(F_x\) and \(F_y\) according to Eqs. 4 is the analytical or component method. It is the approach used most commonly in textbooks for adding vectors.

Note that subtracting a vector is the same thing as adding a vector of the same magnitude in the opposite direction.

**Graphical Vector Addition**

There are two methods of adding vectors graphically. One way is the triangle method, where the second vector that is added to the first is drawn with its tail at the head of the first vector, as shown in Figure 3.

The vector sum or resultant of the two vectors \(\vec{a}\) and \(\vec{b}\) is the vector drawn from the tail of \(\vec{a}\) to the head of \(\vec{b}\).

![Figure 3 Triangle method of graphical vector addition. (Head-to-tail)](image)

In cases where the tails of the vectors share a common point a better technique is the parallelogram method as shown in Figure 4. As drawn these vectors are two adjacent sides of a parallelogram. Parallel lines of equal length can be added as shown to complete the parallelogram. The resultant is then the diagonal from the common tail point to the opposite corner. In practice you only need one of the other sides of the parallelogram. In essence, this is a variation of the triangle method; you are redrawing one of the vectors so that you can complete the correct triangle.
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Figure 4 Parallelogram method of graphical vector addition. (Tail-to-tail)

As with numbers, vector addition is a binary process (you add two at a time) and it is commutative (the order doesn’t matter). This graphical method can be used for more than two vectors; add any two, then add the third to the resultant, and continue until you run out of vectors.

To get accurate results in graphically adding vectors, you must draw the direction and magnitude of the vectors as precisely as possible. For this reason, the parallelogram method is better than the triangle method because you want to depict the angles measured in the same coordinate system. The way to do this is in practice is to use a straightedge and drafting triangle as shown in Figure 5.

Figure 5 Using a triangle and straightedge to move a vector.

The drafting triangle is a right triangle, with two sides and a hypotenuse. Label the longer side \( \text{edge } #1 \) and the shorter side \( \text{edge } #2 \).

Take these steps to graphically add two vectors using a straight edge, triangle, and compass, assuming that the vectors are already drawn tail-to-tail:

1. Align \( \text{edge } #1 \) with the vector to be moved, \( \vec{a} \). The vertex opposite \( \text{edge } #1 \) should be pointed in the same general direction as the vector to be added to, \( \vec{b} \).
2. Put the straight edge along \( \text{edge } #2 \).
3. Slide the triangle and the straight edge as one unit along the length of \( \vec{a} \) until the tip of the arrow depicting \( \vec{b} \) falls on the adjoining line of the triangle and the straight edge.
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4. Holding the straight edge in place, slide the triangle along the straight edge until the right angle outer vertex (where the lines containing edge #1 and edge #2 intersect) coincides with the head of the vector to be added to. (Second picture in Figure 5.)

5. Draw a line along edge #1 at least as long as $\vec{a}$.

6. Fix the radius of a drawing compass to be the length of the originally drawn $\vec{a}$.

7. Mark this length along the line drawn in step 5, starting at the tip of $\vec{b}$.

Try this process with Figure 4.

Experimental Technique

Static friction in the pulley bearings can keep the pulleys from transferring the full amount of tension to the ring. The equilibrium position of the ring is made uncertain by the randomness with which static friction manifests itself in the system. Before passing final judgment on the equilibrium position of the ring, it is good experimental practice to lightly nudge one of the weights a few times. This gives the system a chance to assume its most appropriate configuration and thereby yield the most accurate results.

Vectors and Uncertainty

Two numbers, the magnitude and the direction, are needed to measure a 2D force vector $\vec{F}$ as in today's experiment. Both of these numbers will have uncertainties associated with them:

- the uncertainty in the magnitude, $u(\|\vec{F}\|) = u(F)$
- the uncertainty in the direction $u(\theta)$

These uncertainties are used to express the uncertainty in the vector $u(\vec{F})$, which is also a vector. But we want to express this vector uncertainty as a single number, that is, a scalar, not a vector. So we report the magnitude of the uncertainty vector, which is different from the uncertainty of the magnitude of the vector $u(\vec{F})$. This is a calculated value, given by

$$u(\vec{F}) = U(F) = \sqrt{(u(F))^2 + (F \cdot u(\theta))^2}$$

(6)

Here we have introduced the shorthand convention of using a capital U to mean the magnitude of the uncertainty of a vector.
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An experimental value of \( u(\theta) \) is determined by finding the smallest change in angle of the pulley that disturbs the equilibrium position of the ring around the peg. Similarly, we get a value of \( u(f) \) by finding the smallest mass that can be added to the weight hanger that moves the ring.

Propagating the error of the net force in Eq. (2), we get

\[
U(F) = \sqrt{[U(f_1)]^2 + [U(f_2)]^2 + [U(f_3)]^2 + [U(f_4)]^2}
\]  

Because we expect friction to be the dominant source of error and because the amount of friction in any particular pulley is expected to vary linearly with the size of the supported load, it is reasonable to assume that the relative (percentage) errors of all four forces will be equal. Let’s call this ratio \( \kappa \) (kappa):

\[
\kappa = \frac{U(f_n)}{f_n}, n = 1,2,3,4
\]  

Combining Eqs. 7 and 8 gives the uncertainty of our resultant \( F \):

\[
U(F) = \kappa \sqrt{(f_1)^2 + (f_2)^2 + (f_3)^2 + (f_4)^2}
\]  

Once this is known, we can determine if our experimental observations are consistent with the predictions of Newton's second law. That is, we compare the magnitude of the resultant with zero.

Procedure

You need the following items:

- force table
- slotted mass sets (at least 2)
- triple beam balance
- drafting triangle
- straightedge (ruler)
- drawing compass
- protractor
- colored pencils

Your instructor assigns to each student group specific values in degrees for \( \theta_1 \) and \( \theta_2 \) when the workstations are assigned. Your objective is to center the ring by varying the four load masses and the two remaining pulley positions (angles).

1. Position two pulleys at the assigned angles. These pulley positions must remain fixed during the experiment.

2. Choose initial values for \( \theta_3 \) and \( \theta_4 \), with \( \theta_3 < \theta_4 < \theta_2 \). Follow the allowed ranges on the screen. (That is, \( \theta_3 \) and \( \theta_4 \) cannot be within \( \pm 15^\circ \) of exactly opposite the first two angles.) Position the two
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remaining pulleys at these angles. Place the ring over the central peg and run the support strings over the pulleys.

3. Add to each hanger some initial additional mass (between 100 and 300 g).

4. Adjust the four masses and θ₃ and θ₄ to get the ring in its proper equilibrium configuration. Keep the added mass to any one hanger greater than 100 g and keep the angles within the allowed ranges.

5. Choose one of the four masses. Determine the smallest mass that appreciably changes the equilibrium over the peg. Record this mass increment as $u_i f_n$, where n is the number of the mass you chose.

6. Remove the mass increment. Now, for the same mass, find the smallest change in angular position of the pulley that disturbs the equilibrium. Record this $u_i \theta_{n'}$ in degrees.

7. Return the system to its proper equilibrium position. Nudge the weights a few times to overcome static friction to make sure the system returns to its proper configuration. Fine tune the angle and masses as necessary.

8. When finished, record the angles in degrees.

9. Remove each hanger with its associated weights and measure the total mass (the hanger and everything on it) that had hung from each string, using the balance. Record the values of each of the four masses in grams.

Why not just add everything up and record that number? It would be a lot simpler. But in terms of experimental technique and establishing protocols, we always want to make an absolute distinction between observation and analysis, between measurement and calculation, no matter how trivial that calculation. We need separate records of all measurements and all calculations so we that can go back and check if needed.

Analysis

Again, use gram-weights (g) as the force unit in your calculations, not newtons or dynes. Note that all of the following is a part of your Data Analysis and is not raw Data. (It does not go on your data sheet.)

1. On a blank sheet of paper (not your data sheet) plot a vector diagram showing the x- and y-axes in one color and the force vectors $f_1, f_2, f_3$, and $f_4$ in separate colors. (All vectors start at the origin.)
   a. Use an appropriate scale factor like 1 inch = 100 g.
   b. Use decimal inches on the ruler.
   c. Leave enough space around the diagram to use the parallelogram method to determine the net force vector.

2. Use the parallelogram method to find a graphical indication of F.
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a. There are two vector additions you need to perform here, the first two, then the remaining two. If you were to attempt to add the results of these two operations, it would be difficult; you would have two large vectors that are close to 180° apart, making a very thin parallelogram.

b. Draw and label the resultant of each of these operations (each having a different color). The color of the moved side of the parallelogram should be the same as the original side.

c. **You must finish this and hand it in to the TA by the end of class.**

d. Draw and label the resultant of each of these operations (each having a different color). The color of the moved side of the parallelogram should be the same as the original side. In your *Experimental Results and Conclusions* discussion, you must comment on how close these two results are equal and opposite.

3. There is no template for this experiment. Starting from the Excel Template> generic lab spreadsheet, input your data in shaded cells, with adequate headings and clear indications of what units each quantity are in.

4. Use the component method to sum the vectors $\overrightarrow{F_1}, \overrightarrow{F_2}, \overrightarrow{F_3}$, and $\overrightarrow{F_4}$, obtaining the resultant vector $\overrightarrow{F}$.

5. Use Eqs. 6, 8, and 9 to calculate the magnitude of the uncertainty in the net force, $U\{F\}$.

6. Is $F$ consistent with Newton's second law to within experimental uncertainty?

**Vector diagram in Excel**

7. In the spreadsheet, plot the calculated components of the forces as single points.

   g. There are 4 points. Highlight your x- and y-components (They should be in adjacent columns.), Click on Insert> Charts> Scatter> Scatter with only Markers.

   h. Click on Chart Tools> Design> Chart Layouts> Layout 1.

   i. Move and resize the graph. Enter appropriate chart and axes titles.

   j. Click on Chart Tools> Layout> Insert> Shapes and choose the single-headed arrow (Figure 6).

   Figure 6 Navigating to a Drawing Toolbar arrow to place on a graph.
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k. Draw an arrow from the origin to one of the four points.

l. Repeat this for the other 3 points.

m. With the chart still selected, click on Insert> Text Box then click near the head of one of the arrows. Type in a descriptor such as f1. (All of the formatting is the same in a text box, so you can’t have subscripts.)

n. Repeat this for the other 3 arrows or copy a text box (Ctrl click and drag the border of a box.) and edit the contents.

Questions

1. If all the hangers have the same mass, is it possible to neglect their weights because their contributions “cancel out” when the vector forces representing the string tensions are added together? Explain

2. Propagate the error of the expression a=gh/L, where g is a constant and h and L are measured quantities having uncertainties u{h} and u{L}, respectively.

Newton's Laws of Motion (last edited December 29, 2011)

Dr. Larry Bortner

Learning Objectives

Demonstrate Newton’s second law by determining that the accelerations of objects acted on by two different forces are equivalent to the acceleration determined by force analysis.

Purpose

To demonstrate and verify Newton’s laws of motion.

Background

Sir Isaac Newton was the first to present us with an objective means of predicting the motion of an object under the influence of some force.

☐ His first law tells us that any change in straight-line motion of an object requires a force.

☐ The second law quantifies the force and the change in motion and is summarized in the equation
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(1) \[ \vec{F} = m \vec{a} \]

where \( \vec{F} \) is the resultant (net) force acting on an object of mass \( m \) and \( \vec{a} \) is the acceleration that results.

The third law states that for two bodies interacting with each other but nothing else, any force that body number one exerts on the body number two must be accompanied by an equal force from body number two exerted on body number one in the opposite direction.

There are a couple of items of information embedded in Eq. 1 that you should be aware of, which are also mentioned in the Vector Forces experiment:

- If there is no resultant force, the object will not accelerate (i.e., will either remain at rest or in uniform linear motion).

- It is a vector equation, indicating that \( \vec{F} \) and \( \vec{a} \) are in the same direction.

In this experiment we use Eq. 1 to predict the motion of two different masses, each under the influence of two different forces at separate times. We then verify the predictions using an air track.

An air track permits cars or gliders of various masses to move linearly along its length, and it offers very little frictional resistance to motion. This simplifies the determination of the resultant force on the car, which is the externally applied force minus frictional force. The air track is also equipped with a low friction air pulley.

**Theory, First Force: Gravitation on an Inclined Plane**

One way of applying an external force to a car on the air track is to raise one end of the track by putting an aluminum block or shim under the support at one end. This creates an inclined plane. The forces in this system are shown in Fig. 1, with an exaggerated angle.

![Figure 1 Force diagram of inclined plane. Aluminum blocks are not shown.](image)

If the track of length \( L \) between the legs is raised at one end by a height \( h \), then the angle of inclination \( \theta \) can be found from:

\[ \sin \theta = \frac{h}{L} \]
Since the frictional force is negligible, the only force acting on the car is the gravitational force. The component of this force parallel to the track is given by:

$$F = mg \sin \theta = \frac{mgh}{L}$$  
(3)

where \( m \) is the mass of the car and \( g = 9.80 \text{ m/s}^2 \) is the acceleration due to gravity. Apply Eqs. 1 and 3 to this system:

$$F = ma$$

$$\frac{mgh}{L} = ma$$  
(4)

We have used Newton’s Second Law to predict that that the theoretical acceleration down the frictionless inclined plane is

$$a = \frac{gh}{L}$$  
(5)

Note that the mass of the car does not appear in our theoretical formulation of Eq. 5, indicating that the acceleration of an object on a frictionless inclined plane is independent of its mass. This is because the force exerted on the object (Eq. 3) is proportional to the mass of the object and the mass cancels from both sides of the equation in Eq. 4.

**Theory, Second Force: Tension from a Falling Mass**

Figure 2 Accelerating the car horizontally with a falling mass.

Another method of applying an external force to the car is by adding a known mass \( m_{\text{drop}} \) to the free end of a tape that is attached to the car and that runs over a pulley at one end of the track. This situation is pictured in Fig. 2. Assuming that the tape is massless and that the friction over the pulley is negligible, the tension \( T \) on the tape is the same throughout its length. (If it were not, consider what would happen to a section of the tape somewhere near the middle. Address this scenario in your Conclusions.) \( T \) is the resultant force on \( m \) and pulls the glider along the track toward the pulley. Consequently, Eq. 1 applied to \( m \) is:
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\[ T = ma. \]

Of course, the tension also acts on the dropping mass \( m_{\text{drop}} \), its effect being to hold it up. In fact, the tape’s tension clearly holds the two masses together, pulling each toward the other so that they go no further apart. The second force acting on \( m_{\text{drop}} \) is that due to gravity \((=m_{\text{drop}}g)\), pulling down. So the resultant force on \( m_{\text{drop}} \) is \( m_{\text{drop}}g - T \) downwards. Since the tape does not stretch, \( m_{\text{drop}} \) accelerates downwards with acceleration \( a \). Therefore, Eq. 1 applied to \( m_{\text{drop}} \) is:

\[ m_{\text{drop}}g - T = m_{\text{drop}}a. \]

Eliminating \( T \) between Eqs. 6 and 7, we can calculate the acceleration of the car. This gives our theoretical prediction for the acceleration due to the second type of force:

\[ a = \frac{m_{\text{drop}}g}{m_{\text{drop}} + m}. \]

**Measuring Acceleration**

In order to verify Newton’s Laws, we look at the theoretical predictions of Eqs. 5 and 8 and determine that what we need to experimentally is to measure the acceleration of a car traveling along the air track. The method we’re familiar with from the Falling Bodies experiment would be to measure the time it takes for the car to travel various distances then to plot velocity vs. time. The calculated slope would be our experimental acceleration. However, in the spirit of investigation and expanding our horizons, we’ll find the acceleration a different way.

We use a different equation of motion for an object under a constant acceleration than the one we used previously. (It is important to note that these equations are independent of Newton's Laws.) If the car travels a distance \( x \) starting at rest, the square of the theoretical speed \( v \) at this point is

\[ v^2 = 2ax \] \( \text{theoretical} \)

A plot of \( v^2 \) vs. \( 2x \) then gives the experimental acceleration.

To find the experimental velocity, attach a flag of known length to the car. This flag interrupts the beam in a photogate when the car passes through it. The instantaneous velocity \( v \) of the car at the detector when the flag is halfway through is the average velocity over the total time \( t \) that the beam was broken,

\[ v = \frac{\text{flag}}{t} \] \( \text{experimental} \)

The direction of both of the two types of forces is going left to right as you’re facing the air track. A photogate is set up at the right end of the track. To determine the distance traveled \( x \), we need the initial and final positions of the car. The initial position is simple enough. Where the car breaks the photogate beam determines the final position.

Define \( x_1 \) as the position of the car as it goes through the photogate from left to right, when the flag first interrupts the photobeam (the timer starts timing).
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Define $x_2$ as the position of the car as it goes through the photogate from left to right, when the flag no longer interrupts the photobeam (the timer stops timing).

![Diagram showing the positions of the car to record. $x_0$ is the starting position, $x_1$ is the position where the car’s flag first breaks the photobeam, and $x_2$ is where the beam is first reestablished.](image)

The position of the car when it has the velocity $v$ in Eq. 10 is the average of the positions when it enters the photogate ($x_1$) and when it leaves ($x_2$). The flag length is the difference between the two positions.

Measure the position of the glider where its left edge aligns with the metric ruler that is set in the air track. Note that the positions $x_1$ and $x_2$ are different for each car but are the same for both forces acting on a single car.

When a car starts at zero velocity at the initial position $x_0$ (measured from the left edge!) and accelerates through the photogate, double the distance traveled from the start point to where the flag is halfway through the photogate is

$$2x = 2 \left[ \frac{(x_2 + x_1)}{2} - x_0 \right] = x_2 + x_1 - 2x_0 .$$

(11)

The error in this calculation is

$$\Delta x \approx 2.5 \cdot \Delta x \{x\}$$

(12)

Procedure

You need the following items:

- air track
- photogate
- digital calipers
- metric tape measure
- 2 cars (gliders) of unequal mass with flags (aluminum inserts on top)
- 3 binder clips
- piece of string with tied loops at both ends
Reforming the intro physics lab to impact SR

- various aluminum blocks
- triple beam balance
- Computer with ScienceWorkShop interface

Note: Never mark the surface of the air track. Even the thinnest layer of ink or graphite significantly adds to the friction. Scratching the surface disrupts the air flow, which can slow things down.

Basic Measurements

1. The photogate should be just to the right of the crossbar at the right end of the air track.
   a. For each car, measure and record the positions \( x_1 \) and \( x_2 \), in meters (not millimeters, not centimeters), with the side of the car marked with an X facing out. Again, \( x_1 \) is where the car first causes the timer to start, then \( x_2 \) is where the timing first stops after you slide the car through the photogate from left to right.
   b. The numbering on the rule on the track can be confusing. There are little 1m’s and 2m’s at strategic locations meaning that the position is one or two meters plus the larger numbers indicating the millimeters or centimeters that you are reading.
   c. Do not move the photogate during the experiment. The values of \( x_1 \) and \( x_2 \) for each car should be the same for the second force as for the first force.

2. Measure and record the masses of your two cars, with flags attached and with a clip on the flag.

3. Press the mm/in button to turn on the digital calipers display.
   a. With the caliper jaws closed, press the 0 button to get a zero display.

4. Choose a number (1-5) of aluminum blocks to place under the single foot at the left end of the track. This raises that end a distance \( h \). Measure \( h \) (the thickness of the blocks stacked together) with the calipers, and record this number.

5. Using the tape measure, measure and record the distance \( L \) between supports of the air track (where it touches the table; refer to Fig. 1). Record your estimated uncertainty.

6. Turn on the air and make sure the track is level. A glider will drift a little back and forth on a level track. Consult your TA if the glider accelerates to one end. Do not attempt to adjust the air track yourself.

7. Place the blocks under the left end support of the track.

8. Click on Data Studio Experiments> First Quarter> Newton’s Laws timer to start the DataStudio program.
   a. Click on the Start button to start the timer.
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b. Leave it running for the rest of the experiment. It automatically resets, displaying the last elapsed time that the photobeam was interrupted.

Experiment, First Force: Gravitation on an Inclined Plane

9. Position the left edge of the small car at the 2.150 m mark. This gives you a distance of a few centimeters to the photosensor. This is your first initial position (release point), \(x_0\).

a. Record this position in meters. (The air track is over 2 \(\frac{3}{4}\) meters long and as noted previously, the whole number of meters on the rule is not as prominent as the centimeter numbers. Don’t miss this number.)

b. Release the car. Be careful not to impart any sideways movement or bounce to the car, as this would cause the car to touch the track and introduce friction.

10. Stop the car before it goes back through the photogate. Record the displayed time.

11. Repeat the timing procedure in Steps 9 and 10 nine more times for the same starting position \(x_0\). The standard deviation \(u_t\) of the ten times for this distance is the estimated absolute error for all subsequent measured times in this experiment.

12. Make single time measurements for seven more different release points spread out evenly over the length of the air track. One of these release points should be at the extreme left of the track where the car bumper is not quite touching the air track bumper. The points should be about 30 centimeters apart. This gives you eight total release/time points.

13. Switch to the other car and choose eight release points different from those of the first car. Record these positions and measure and record the times (single measurements).

Experiment, Second Force: Tension from a Falling Mass

14. Turn off the blower and remove the aluminum blocks from under the air track.

15. Place one of the cars at the end of the track near the pulley.

16. Measure the mass of the fishing float \(m_{\text{drop}}\) that will be used to accelerate the cars.

17. Choose one of the gliders and completely un-wrap the string that is around the flag.

18. Attach the float to the string.

   a. Push down on the plastic cylinder that sticks out of the float to reveal a metal hook.

   b. Thread the string through the hook so that when you release the cylinder it will clamp down on the string and hold the float securely.

19. Place the glider on the air track with its X facing out and run the string over the pulley.
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a. With the glider at its $x_2$ position, the float should be just above the floor but not touching it.

b. If necessary, reposition the float on the string to meet this condition.

20. Choose eight different release points spread out evenly over the extent of movement (about 12.5 cm apart). Measure the time it takes to accelerate through the photogate from each of these points.

21. Repeat this for the other car, using the same release points.

22. When you are finished taking data for a car, please wrap the string around the aluminum flag and affix the free end of the string to the double stick tape on the edge of the glider.

Analysis

1. Click on Excel Templates> First Quarter> Newton’s Laws to load the Excel template.

Data Entry

2. Enter in the following:
   a. the values of $h$ and $L$ and their uncertainties,
   b. the uncertainty $u\{x\}$ in a car position,
   c. the beam-breaking positions $x_1$ and $x_2$ for both cars.

3. For the small car, enter in the starting position and the ten times you measured in Steps 9-11 of the Procedure.

4. Enter in the eight pairs of position and time points for both cars for the first force.

5. For the second force, enter in the masses and the eight pairs of position and time points for both cars.

Calculations and Comparisons

6. Convert any data that is in millimeters to meters.

7. Calculate the theoretical acceleration of a car on the inclined plane from Eq. 5.

Calculate the error of this value from

$$u\{a\} = a \sqrt{\left(\frac{\Delta h}{h}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}.$$ 

8. Determine the uncertainty $u\{2x\}$ from Eq. 12.
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9. Calculate the average time and the standard deviation $u\{t\}$ for the ten times of the small car at the same release point.

10. Calculate the flag length and its uncertainty for both cars.

11. Put formulas for $2x$ (Eq. 11), the experimental speed squared $(v^2$ using Eq. 10, not Eq. 9), $u\{v^2\}$, $v^2 + u\{v^2\}$, and $v^2 - u\{v^2\}$ in H4, I4, J4, K4, and L4. Be sure to use absolute cell references where appropriate because these formulas are going to be copied. The expression for $u\{v^2\}$ is

$$u\{v^2\} = 2v^2 \sqrt{\left(\frac{u\{flag\}}{flag}\right)^2 + \left(\frac{u\{t\}}{t}\right)^2}$$

a. Highlight these five cells and copy them.

b. Click in H19 and paste. All five formulas should be copied to the first row of the big car data and calculations done for the first starting position and its time. The formulas have to be corrected but we'll do that in Step 10e.

c. Click in H52 and paste. Again, five numbers appear, but these are the correct calculations.

d. Before clicking anywhere else, click on the lower right corner of the five cell selection, drag down to J59, and release. You've just done the calculations for the small car for the second force.

e. Return to H19 and correct the formulas in this row as needed.

f. Select the five cells with formulas in that row and copy them.

g. Go to H66 and paste.

h. Copy these cells down to row 73. If you scroll down, you'll find that the $v^2$ vs. $2x$ data has been plotted for the second force. You should have two lines with obviously different slopes.

i. Copy the cells down for the small car and the big car for the first force.

12. Although the plots are automatic, you still have to add the error bars. The X Error Bar of $u\{2x\}$ is a single Fixed value: for both plots. The $u\{v^2\}$ values have to be entered as Custom (+ and -).

13. These graphs should be straight lines, since $v^2=2ax$. The slopes of these lines are the corresponding accelerations.

14. Find the least squares slopes $a_{exp}$, and $a_{exp}$ of $v^2 + u\{v^2\}$ vs. $2x$ and $v^2 - u\{v^2\}$ vs. $2x$. You need just the slope, nothing else. This is one of the few times where you can use LINEST without adding the 1 and 1 at the end and hitting Shift/Control/Enter.

15. Find the average of these two slopes for the experimental value of $a$.

16. The standard error of these two values is $u\{a_{exp}\}$.
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17. Copy the four formulas. Paste into cells G29, G62, and G76. You have just finished the similar calculations for the other three data sets.

18. Are the accelerations of the two cars due to the first force equal to each other within the accuracy of the experiment?

19. Compare both of these accelerations separately to the theoretical value of an object on an inclined plane.

20. For the second force, calculate the theoretical acceleration for both cars from Eq. 8 and compare to your experimental values from the least squares fit. Use the following expression for the uncertainty of the theoretical acceleration due to the second force:

\[ u\{a\} \approx \frac{u\{m\}}{m_{\text{drop}}} \]

Questions

1. If the string used to connect the small weight to the car in Part 2 had appreciable mass, would the car still undergo uniform acceleration? Explain.

2. The experimental value of the acceleration depends differently on the mass of the car for the first force than it does for the second force. Explain how this difference comes about.

Centripetal Force (last edited December 29, 2011)

Dr. Larry Bortner

Learning Objectives

Define the form of a centripetal force using both linear speed and angular speed.

Explain how a centripetal force varies with the radius of the orbit.

Purpose

To show that a constant force acting at a perpendicular direction to the velocity of a mass results in uniform circular motion.

Background

In the analysis of motion, velocity is how fast an object’s position is changing and acceleration is how fast the velocity is changing. Both of these quantities are vectors, meaning that in two dimensions two
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numbers such as magnitude and direction are needed for unique identification. For something going around in a circle at constant speed (undergoing uniform circular motion), the direction of its velocity is changing. Since a direction is needed to fully define the physical quantity of velocity, the velocity is changing and there has to be an acceleration.

The direction of this acceleration is towards the center of the circle. Centripetal is the word we use to describe both the acceleration and the force required to change the straight line motion. For an object of mass \( m \) in uniform circular motion with speed \( v \) a distance \( r \) from a non-moving center, the centripetal force is

\[
F_c = m v^2 / r = m \omega^2 r
\]

where \( \omega = v / r \) is the angular velocity.

This experiment compares the calculated centripetal force on a rotating mass that stretches a spring a given distance with the measured static force that stretches the spring the same distance.

![Figure 1 The centripetal force apparatus.](image)

The concept and use of the experimental apparatus (Fig. 1) are as follows:

- Hang a mass freely at a given radius.
- Stretch a spring attached to the mass from the center with a known weight.
- Match that stretch by rotating the mass at a specific frequency.
- A power supply rotates the system.
- The spring is in the center so we don’t have to worry about the effect of its mass.
- Use the Science Workshop interface to measure the rotation and calculate the angular velocity.

Rearranging Equation 1, we have that

\[
\omega^2 = F_c (1/mr)
\]

The experimental realization of this is that if we plot \( \omega^2 \) vs. \( 1/mr \), we get a straight line with slope equal to the centripetal force.
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Procedure

You need the following items:

- Leader power supply and banana leads
- 3-beam balance
- mass hanger
- Science Workshop interface
- computer with Centripetal Force program
- rotating platform with base, rotary motion sensor, and motor

For this experiment to work properly:

- The hanging mass support string from the side post must be adjusted so that the string from the mass to the central pulley is horizontal.
- When the spring is stretched statically, the weight must hang vertically. Denote the static load by $F_L (= m_L g)$.
- The apparatus must be level to get good data.

1. Click on Data Studio Experiments> First Quarter> Centripetal Force.

2. Make sure that the FINE and COARSE knobs controlling the VOLTAGE on the Leader power supply are full CCW (counter-clockwise).
   a. Turn on the power supply.
   b. The display should read 0.00.

3. Weigh and record the mass in grams of the hanging brass object. This is the mass that will be going around in circles. You may have to disconnect the string coming from the center.
   a. Also record the 50-g mass of the mass hanger (the load) as $m_L$. As noted, its weight (calculated in the Analysis) is $F_L$, the static load which should also be the value of the centripetal force.

Finding the angular velocity for a single orbital radius

4. The next step is to set the initial radius of the mass’s circular orbit. Set the position of the side post to 6.0 cm (where the vertical line of the side post aligns with the ruled markings). Record this setting in cm. (The center post must be at zero.)

5. To reconnect the brass mass, hang it on the string hanging from the side post. Make sure that the string attached to the spring goes under the pulley on the center post. Loop this string around the hook on the mass that has the screw and washers. This connection is secured by tightening the screw to compress the string. But don’t tighten it yet.

6. Hang the mass hanger over the clamp-on pulley at the end of the bar and connect it to the hanging brass piece.
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7. For the brass object to hang vertically, adjust the spring bracket on the center post so that is near the top...
   a. Pull the loose end of the string so that the hook of the hanging mass is touching the pulley on the center post.
   b. Now tighten the screw (finger-tight) to secure the spring-to-mass connection.
   c. Adjust the spring bracket so that the two strings supporting the brass mass are aligned with the vertical line on the side post. This is the fine adjustment of the radius. As you increase the orbital radius, once or twice you may have to change the effective length of the string by loosening the screw on the brass object. When you do this, return the spring bracket to the top. This screw adjustment is just a rough adjustment. As noted, use the spring bracket for finer adjustment.

8. Align the indicator bracket on the center post with the orange indicator.

9. Remove the mass hanger and its string.

10. By using the coarse voltage adjust on the power supply, slowly increase the voltage to about 2.2 volts. The platform will start rotating. Using the fine voltage adjust, increase the voltage until the orange indicator is where it was in the previous step.

Note: the response time of the rotating platform may be 2 to 5 seconds behind your change in voltage. Be sure the indicator stays in the desired position for several revolutions.

11. Click on the Start icon at the top. Click on Stop after ten readings.

12. Record the mean angular velocity, its standard deviation, and the count.

13. Estimate $u/r$. You can state the post-to-post distance to a millimeter or better. But $r$ is the radius of the orbit of the brass mass as it whirls around. Are both posts vertical? Was the mass hanging exactly vertically when you put on the static load? Did you place the indicator bracket exactly where the orange marker was? Was the angular velocity the exact velocity that returned that orange indicator to that exact same point? Did it stay there?

14. Repeat steps 4-12 for these radii in cm:
   a. 6.5
   b. 7.2
   c. 8
   d. 9
   e. 10.3
   f. 12
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14.4

18

24

There’s about 10 cm of play for the spring bracket so you’ll only have to do steps 7a and 7b for one of these radii, maybe two.

15. Quit the DataStudio program and don’t save the activity. As you analyze your data in a spreadsheet, you may realize that you have to retake some data. If that is the case, simply restart the program.

Analysis

<table>
<thead>
<tr>
<th>m (g)</th>
<th>m₀ (g)</th>
<th>F₀ (N)</th>
<th>r (cm)</th>
<th>ω</th>
<th>σ{ω} (rad/s)</th>
<th>count</th>
<th>u{ω} (rad/s)</th>
<th>1/mr (kg⁻¹·m⁻¹)</th>
<th>ω² (rad/s²)</th>
<th>u{1/mr} (kg⁻¹·m⁻¹)</th>
<th>u{ω²} (rad/s²)</th>
</tr>
</thead>
</table>

1. Set up a generic spreadsheet with entries as illustrated here.

   a. Use the Insert Symbol button Ω for the Greek letters.

   b. The quantities in the second column are measured or evaluated once and hold for the entire experiment. m is the mass of the brass thing hanging from the string and m₀ is the total mass used to stretch the spring statically.

2. Fill in the tables with your data.

3. Do the necessary calculations with the appropriate Excel formulas, including the units conversions.

4. Propagate the absolute errors in 1/mr and ω².

5. In the error columns, calculate these errors in 1/mr and ω².

6. Plot ω² vs. 1/mr, with error bars.

7. Do a least squares fit with errors to get F₀ and u{F₀}.

8. Compare F₀ to F₀.
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1. Why is it crucial that the string from the mass to the pulley is purely horizontal and that the support string hangs straight up and down?

2. When the radius is increased, does the period of the circular motion increase or decrease? Explain.

Momentum and Energy in 1D Collisions (last edited December 29, 2011)

Dr. Larry Bortner

Learning Objectives

Define what an elastic collision is.

Explain what is conserved in elastic and inelastic collisions.

Purpose

To investigate how momentum and kinetic energy change in collisions.

Background

Newton's second law of motion states that the force exerted on an object is proportional to the resulting acceleration, with the constant of proportionality being the mass. The equation form of this is \( F = ma \). Another way of stating this is that the force is how the momentum \( p = mv \) changes with time. This equation is

\[
F = \frac{dp}{dt} = \frac{\Delta p}{\Delta t}
\]

(1)

where the derivative form is exact and the delta formulation is good for small time increments.

When two objects A and B interact, their velocities change. (Think two pool balls colliding or a linebacker hitting a running back.) We can consider these objects to be a system, which is an object or a thing in and of itself. Under such consideration, if no force acts on the system, the system's momentum (the sum of the individual momenta) does not change. If some thing is just sitting there, it’s not going to jump up and start moving unless sufficiently prodded.

In our system of two objects, the momentum of A changes if B exerts a force on it. Does the system momentum change when this happens? We know from Newton's Third Law that if B exerts a force on A, A exerts the same force on B in the opposite direction. Then the changes in momentum are equal and opposite and the sum of the two momenta remains the same before and after the interaction. Or, to coin a phrase, momentum is conserved.
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Energy is another quantity that is conserved, but it can take many forms and is harder to measure. In the special case of an elastic collision, the only type of energy involved is kinetic. Since energy must be conserved and it can’t transform to anything but kinetic after a collision, by definition an elastic collision is one where the kinetic energy is conserved.

The force between two objects is labeled as conservative if the interaction is elastic or dissipative if it is inelastic (kinetic energy is not conserved). A perfectly inelastic collision is one where the two objects stick together after impact. It is important to note that independent of what's happening with the kinetic energy, momentum is always conserved.

The experiment you are conducting today explores momentum transfer and kinetic energy balance in elastic and inelastic collisions of two cars (also called gliders) of different mass on an air track. Both cars have constant velocities before and after the collision. To simplify matters, one of the cars is at rest before the collision. For the elastic case, this still leaves three velocities to determine:

1) The velocity before impact of the incoming car.
2) The velocity after impact of the incoming car.
3) The velocity after impact of the car that gets hit.

For the perfectly inelastic collision, just two velocities are needed:

1) The velocity before impact of the incoming car.
2) The velocity after impact of the car that got hit (which is also the velocity of the car that hit it since they’re stuck together).

To gather the time data needed to determine these velocities, we use two photogates (Fig. 1) connected to a computer interface that can use software timers.

Figure 1 Impact point of the two cars. Note that both flags are inside the photogates.

Note that even though the cars are confined to move in a single dimension defined by the air track, direction is still important. We use the intuitive convention that the velocity going to the right as we view the air track is positive and that going to the left is negative.
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To approximate an elastic collision, the gliders contact through metal spring bumpers. The completely inelastic collision, where the objects stick together after contact, is modeled experimentally with velcro glued to the ends of the gliders (hooks on one, loops on the other).

When the photogate is powered up, an infrared beam is transmitted between an emitter and sensor. When the beam is broken (interrupted), the timer starts and runs until the beam is restored. A metal flag of known length on top of each glider breaks the beam when the car goes through the photogate. The time that the car flag interrupts the gate can give the speed. For example, if a 5 cm flag interrupts the beam for 1 s, the glider it is attached to is traveling at 5 cm/s.

Let \( P = mv + MV \) stand for the total momentum of the two-car system, where \( m \) and \( v \) are the mass and velocity of the small car, \( M \) and \( V \) the mass and velocity of the large car. One mathematical way of stating momentum conservation is the obvious: \( P_{\text{after}} = P_{\text{before}} \).

Another way is to define the ratio

\[
\rho = \frac{P_{\text{after}}}{P_{\text{before}}},
\]

(2)

and say that \( \rho \) has to be unity (equal to one). (Note that \( \rho \) is not a “pee” but the Greek letter “rho,” pronounced “row” as in \( \rho \rho \rho \) your boat.) This expression is better to test experimentally because we can compare many collisions that don’t have the same initial conditions. This quantity should be unity for both elastic and inelastic collisions, falling short of this value when external forces such as friction or gravity are involved during measurement.

We can define a similar ratio for the total mechanical energy \( E \). For the conditions in this experiment, the mechanical energy will be solely the kinetic energy \( K \) (since the track is level, there’s no change in the gravitational potential energy):

\[
\eta = \frac{E_{\text{after}}}{E_{\text{before}}} = \frac{K_{\text{after}}}{K_{\text{before}}},
\]

(3)

(The Greek letter here is not “en” or “aiitch”, but “eta”, pronounced “ate uh” as in Buford \( \eta \) mess of catfish and hush puppies.) This quantity is unity for completely elastic collisions and something less than one for inelastic impacts. For completely inelastic collisions, one can show that

\[
\eta = \frac{m}{m + M}, \text{ small car incoming},
\]

\[
\eta = \frac{M}{m + M}, \text{ large car incoming},
\]

(4)

While the air track approaches an environment of zero friction along a straight line, deviations from the ideal can frustrate our attempts to verify fundamental physical properties. There is some friction and it can vary according to the position on the track. Also, the beam may not be quite level or it may sag ever so slightly in the center, introducing gravitational influences. By recognizing these possibilities, measurements can be planned so as to minimize the effects of external agents.
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To reduce external effects, consider the following points:

1. Ideally, the instantaneous speeds of the gliders should be measured just before and just after impact. We’re not set up to do that. We have to measure average speeds. For something going at a constant velocity, the instantaneous and average speeds are the same. But there's an ever so slight bit of friction, so we need to keep the averaging distance (flag length) small, in this case, about 5 cm.

2. The two photogates must be placed far enough apart so that both flags are “inside” the gates at impact. The timing apparatus can give an accurate measure of the car’s speed as it goes through the photogate. But the farther away from the collision point the car gets, the more chance that friction slows it down.

3. Take a moderate approach to pushing the incoming car towards the crash: not too fast and not too slow. Too fast and the air film breaks during impact and the gliders grind directly against the metal track, in which case an external force acts on the system and momentum won’t be conserved. Too slow and variations in the air flow and track deviations from the horizontal, both of which may depend on where the car is on the track, can change the velocity. A prudent range for the starting velocity $v_{\text{before}}$ of the incoming glider is $100 \text{ mm/s} < v_{\text{before}} < 500 \text{ mm/s}$.

4. To cancel out some of the effects of gravity, measure impacts with the incoming car going first one way then the other. Choose an approximate impact point and conduct your trials with the impacting car incoming from the left. Then have more trials with it incoming from the right, at about the same impact point. If the air track is slightly tilted, the changes in velocity due to gravity should cancel out when the results are averaged.

5. To compensate for a sagging beam, the collision should not take place at or about the halfway point of the track.

Procedure

You need the following items:

- air track
- 2 differently sized air track cars (gliders)
- 2 photogates
- digital calipers
- triple beam balance

Turn on the air supply and play around with the gliders on the track. Get a general sense of what happens in a collision between the two small incoming, large at rest; large incoming, small at rest; both incoming; bumper and velcro collisions. Turn off the air supply before continuing.

Standard caveats:

- Don’t drop the gliders.
- Don’t scratch or mar the surface of the air track or the inside flanges of the car.
- Excessive speed can kill the car or the track. (Well, severely damage either enough to take them out of action.)
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Overview

- You will be recording the times for twenty collisions for the gliders bouncing off each other and the times for twenty collisions when the gliders stick together on impact.
- Ten of the twenty collisions will be with the small car incoming and the large car at rest, the other ten will be vice versa.
- Five of the ten collisions for a particular colliding car will be with it incoming from the left, the other five from the right.

Lengths and Positioning

1) Use the digital calipers to measure the two flag lengths. Record the length of the flag on the small car as l and the length of the large car’s flag as L.

a) Press the mm/in button to turn on the display, zero it with the jaws together, and record the measurement in mm.

b) Estimate the uncertainty of these measurements.

2) Measure and record the mass m of the small car with its flag and the mass M of the large car with its flag. Remember to record the generic mass uncertainty.

3) Place the cars so that their spring bumpers touch at a point that is not within 10 cm of the center of the track.

4) This glider placement should be within the photogates. Adjust the cars or the photogates as necessary so that both flags are just inside the gates as in Fig. 1.

Data Sheet

5) Set up a table with the following headings for the glider times for the elastic collisions. As stated above, there will be twenty trials total.

<table>
<thead>
<tr>
<th>Trial</th>
<th>$t_{\text{before}}$</th>
<th>L/R</th>
<th>±</th>
<th>$t_{\text{after}}$</th>
<th>L/R</th>
<th>±</th>
<th>$T_{\text{before}}$</th>
<th>L/R</th>
<th>±</th>
<th>$T_{\text{after}}$</th>
<th>L/R</th>
<th>±</th>
</tr>
</thead>
</table>

a) Here the lowercase t refers to the small car and the uppercase T to the large car.

b) The subscripts indicate whether the time was before or after the collision.

c) The L/R column is to indicate whether the time is from the Left photogate or the Right photogate and which time. (There may be 1 or 2.)

d) The + (right) or – (left) indicates the direction of the car’s velocity along the track for each recorded time.

6) Set up a similar table for the inelastic collisions.
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7) What is recorded and displayed in the DataStudio table of the program is the elapsed time a photogate beam was interrupted. It does not record:

   a) the direction the car was traveling (to the right or left),
   b) which car it was (gold or red), or
   c) when it occurred (before or after the collision).

   These three conditions must be noted by the observer. (That would be you.)

Elastic Collisions

8) Click on Data Studio Experiments> First Quarter> Momentum and Energy.

9) Turn on the air supply.

   a) Click on the Start button to enable the timer.
   b) Steady the large glider at your predetermined position and launch the small glider from outside its photogate. Let go of the large glider just before impact.
   c) Note that for the car to have a velocity before impact in the target range stated at the end of the Background discussion, the measured times have to be in the approximate range of $0.100 \, \text{s} < t_{\text{before}} < 0.500 \, \text{s}$.
   d) Stop the cars after the post-collision times have been displayed.
   e) Click on the Stop button.
   f) Record from the DataStudio table in the appropriate column on your data sheet:
      i) the times from the DataStudio table,
      ii) the Left or Right photogate and the number of the time (first or second),
      iii) and the direction through the gate.
      iv) Whether the time was before or after the collision, obviously, is determined by the column you put it in.
      v) Record the time as ∞ for the car at rest.
   g) Press Alt plus the minus key to clear the table, then press Enter to verify your choice.
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10) Repeat Steps 9(a)-g) four more times (for a total of five trials). Vary the times $t_{\text{before}}$ evenly throughout the range mentioned in Step 9c so that you have a wide range of incoming velocities. The data in the your table should have the following form:

<table>
<thead>
<tr>
<th>Trial</th>
<th>$t_{\text{before}}$</th>
<th>L/R</th>
<th>$t_{\text{after}}$</th>
<th>L/R</th>
<th>$T_{\text{before}}$</th>
<th>L/R</th>
<th>$T_{\text{after}}$</th>
<th>L/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>#.# L1</td>
<td>+</td>
<td>#.# L2</td>
<td>-</td>
<td>$\infty$ X</td>
<td>X</td>
<td>#.# R1</td>
<td>+</td>
</tr>
</tbody>
</table>

11) Repeat Steps 9-10, switching right and left directions of the colliding car. You want the cars to collide at *about* the same position, but the small car will now be coming in from the right and both flags must still be completely inside the two photogates. Data should look like this:

<table>
<thead>
<tr>
<th>Trial</th>
<th>$t_{\text{before}}$</th>
<th>L/R</th>
<th>$t_{\text{after}}$</th>
<th>L/R</th>
<th>$T_{\text{before}}$</th>
<th>L/R</th>
<th>$T_{\text{after}}$</th>
<th>L/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-10</td>
<td>#.# R1</td>
<td>-</td>
<td>#.# R2</td>
<td>+</td>
<td>$\infty$ X</td>
<td>X</td>
<td>#.# L1</td>
<td>-</td>
</tr>
</tbody>
</table>

12) Repeat steps 9-11, switching the roles of the small car and the large car. That is, the small car is held steady and you run the large car into it, five times from the right and five times from the left. Data table entries should be like this:

<table>
<thead>
<tr>
<th>Trial</th>
<th>$t_{\text{before}}$</th>
<th>L/R</th>
<th>$t_{\text{after}}$</th>
<th>L/R</th>
<th>$T_{\text{before}}$</th>
<th>L/R</th>
<th>$T_{\text{after}}$</th>
<th>L/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-15</td>
<td>$\infty$ X</td>
<td>X</td>
<td>#.# R1</td>
<td>+</td>
<td>#.# L1</td>
<td>+</td>
<td>#.# R2</td>
<td>-</td>
</tr>
<tr>
<td>16-20</td>
<td>$\infty$ X</td>
<td>X</td>
<td>#.# L1</td>
<td>-</td>
<td>#.# R1</td>
<td>-</td>
<td>#.# L2</td>
<td>-</td>
</tr>
</tbody>
</table>

**Inelastic Collisions**

13) Turn both cars around so that the velcro bumpers will contact.

14) Repeat steps 9-12, again starting with the smaller car incoming from the left, switching directions, then switching the large car and the small car.

a) Record only two times for each collision, one for the incoming car before impact and one for the car that got hit after impact. Yes, there are three times listed in the DataStudio table. The time for the incoming car is recorded after impact, but because of friction the calculated speed will be smaller than the speed of the car that got hit.

b) The time for the incoming car after collision is not important but its direction is. Be sure to record this.

c) If the cars don’t stick together, the velcro has exceeded its usefulness; notify the TA.

d) The inelastic collisions data table should look like this:

<table>
<thead>
<tr>
<th>Trial</th>
<th>$t_{\text{before}}$</th>
<th>L/R</th>
<th>$t_{\text{after}}$</th>
<th>L/R</th>
<th>$T_{\text{before}}$</th>
<th>L/R</th>
<th>$T_{\text{after}}$</th>
<th>L/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>#.# L1</td>
<td>+</td>
<td>X</td>
<td>X</td>
<td>$\infty$ X</td>
<td>X</td>
<td>#.# R1</td>
<td>+</td>
</tr>
<tr>
<td>6-10</td>
<td>#.# R1</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>$\infty$ X</td>
<td>X</td>
<td>#.# L1</td>
<td>-</td>
</tr>
<tr>
<td>11-15</td>
<td>$\infty$ X</td>
<td>X</td>
<td>#.# R1</td>
<td>+</td>
<td>#.# L1</td>
<td>+</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
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Analysis

1) Click on Excel Templates> First Quarter> Momentum and Energy. This has all the appropriate headings for data (shaded cells) and calculations. Note that the Excel values for “∞” (1E+99) have already been entered.

2) Enter in your data.
   a) Use the numbers 1 for + and -1 for − to denote the direction.
   b) Note that the spreadsheet format is not the exactly the same as your data sheet. Identifying the photogate is an observational detail used to identify the correct time.
   c) Times and directions not recorded as data for a car should be left either blank or the 1E+99 don’t put in an “X.”

Elastic Collisions Calculations

3) For Trial 1, calculate the momenta \( p = \text{direction} \times m \frac{\text{L}}{\text{T}} \) or \( p = \text{direction} \times M \frac{\text{L}}{\text{T}} \) before and after collision for both cars.
   a) Make the cell references to the length and mass of each car absolute (hit the F4 key).
   b) There should be four complete formulas, including the one for \( p_{\text{before}} \) for the large car. It’s at rest, it should be zero, but that’s why we have the large number as the time, so it calculates out to zero. That way we can copy the formulas to the other nineteen trials.

4) Calculate the experimental ratios \( \rho \) and \( \eta \), also for Trial 1 (Eq. (2) and Eq. (3)). Note that you can express the kinetic energy in terms of the momentum:

\[ K = \frac{p^2}{2m} \]  

(5)

The energy ratio then becomes

\[ \eta = \frac{\frac{p^2_{\text{after(red)}}}{M} + \frac{p^2_{\text{after(gold)}}}{m}}{\frac{p^2_{\text{before(red)}}}{M} + \frac{p^2_{\text{before(gold)}}}{m}} \]  

(6)

5) Select these six formulas that you just entered and copy. (You did remember to use absolute cell reference for the masses in the calculation of \( \eta \), didn’t you?)
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a) Paste these formulas into the corresponding cells for Trial 1 and for Trial 11 for the inelastic collisions. You will have to change some of these later, but it is easier to edit than it is to create from scratch.

b) Select the cells for these quantities for the elastic collisions for Trials 2-20 (19 rows x 6 columns).

c) Paste > Paste Special... > Formulas > OK.

6) Calculate the average and standard deviations of both ratios $\rho$ and $\eta$.

a) Compare $\rho_{av}$ with $\rho_{theory}=1$. For this experiment we'll use a more relaxed value of the standard deviation as the error in the average because the measurements are so precise and the systematic errors so subtle and numerous that it's difficult to quantify them.

i) Can you say that momentum is conserved to within experimental error for your data?

b) Compare $\eta_{av}$ with $\eta_{theory}=1$.

i) Can you say that these collisions were completely elastic? If not, what percentage of kinetic energy was lost?

Inelastic Collisions Calculations

7) We have to make some changes in our momentum calculations.

a) For the first ten trials, $p_{after}$ for the gold car has to be calculated using the speed of the red car. Make this correction for Trial 1 then copy the six formulas down through Trial 10.

b) For the next ten trials, $p_{after}$ for the red car has to be calculated using the speed of the gold car. Make this correction for Trial 11 then copy the six formulas down through Trial 20.

8) Calculate the average and standard deviations of the momentum ratio $\rho$ for all twenty trials.

a) Compare $\rho_{av}$ with $\rho_{theory}=1$.

i) Can you say that momentum is conserved to within experimental error for your data? If not, what was it about the collisions or your measurements that might have altered your data?

9) Calculate the average and standard deviations of the kinetic energy ratio $\eta$ for the first ten trials then the last ten trials.

a) Calculate the theoretical values of $\eta$ for both cases. Use the following expression to calculate the two uncertainties: $\nu(\eta) = \eta \frac{\nu(m)}{m}$.

b) Compare the theoretical and experimental kinetic energy ratios for both cases.
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c) What percentage of kinetic energy was lost in these the two types of inelastic collisions, on average (two numbers)?

Questions

1) Propagate the error in the expression $I = \frac{1}{2} m(r_i^2 + r_o^2)$, assuming $m$ is constant and both $r_i$ and $r_o$ have the uncertainty $u\{r\}$.

2) A compressed spring is placed with a light adhesive between the large car and the small car such that it is touching the facing ends. The binding of the spring is removed and the two cars are thrust from each other with the spring no longer attached to either. What is the ratio of the speed of the smaller car to that of the larger? Use numbers for the cars you used in this experiment.

Angular Acceleration (last edited December 29, 2011)

Dr. Larry Bortner

Learning Objectives

Use digital calipers to measure dimensions.

Explain how a three-beam balance can measure masses greater than one kilogram.

Define moment of inertia.

Discuss the rotational analog of Newton’s second law.

Purpose

To verify Newton’s second law for rotational motion by finding the moments of inertia of a disk and a ring.

Background

Newton's Third Applied to Rotation

The rotational analog to $F = ma$ is

$$\tau = I \alpha$$

where the torque $\tau$ is a rotation-producing quantity, the moment of inertia $I$ is a measure of an object’s resistance to a change in rotational motion, and $\alpha$ is the angular acceleration. To talk about circular motion, one must indicate an axis about which this motion is occurring. At a point a perpendicular
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distance $r$ from this axis, a force $F$ applied at right angles to both the axis and to $r$ results in a torque $\tau = rF$. Likewise, the angular acceleration $\alpha$ is related to the linear acceleration $a$ of the point by $\alpha = a/r$. The mass is a defining property of an object that is a measure of its resistance to a change in linear motion and does not change (in the object’s rest frame). The moment of inertia of an object however, can vary, depending on the distance to the rotational axis as well as the orientation, size, and shape of the object.

Theoretical Moments of Inertia

For an axis going through the center of mass and perpendicular to the circular shape, the theoretical moments of inertia for a disk and ring are:

$$I_{\text{disk}} = \frac{1}{2} m_{\text{disk}} r_{\text{disk}}^2$$

$$I_{\text{ring}} = \frac{1}{2} m_{\text{ring}} \left( r_{\text{inner}}^2 + r_{\text{outer}}^2 \right) ,$$

where the $r$’s are the appropriate radii.

Forces, Friction, Acceleration, and Torque

In this experiment we hang a mass $m$ with a string that is wrapped around a pulley of radius $r$ on the vertical shaft of the rotational apparatus. When let go, the mass accelerates to the floor, causing the disk to rotate. The tension $T$ in the string provides the torque that causes this rotation. Assuming a small frictional force $f$, Newton’s second law applied to the mass gives

$$\sum F = mg - T - f = ma$$

The torque applied to the shaft would be, after solving Eq. 3 for $T$ and multiplying both sides by $r$,

$$\tau_{\text{actual}} = Tr = \tau_{\text{ideal}} - fr = mr \left( g - \alpha \right) - fr .$$

In a frictionless world the ideal torque is

$$\tau_{\text{ideal}} = mr \left( g - \alpha \right)$$

but no matter how well-designed a piece of mechanical equipment is, friction enters in. We could measure the friction and account for it, but that is not the main purpose of the experiment. We want to find an experimental value for the moment of inertia of the object rotating about the shaft.

The torque in Eq. (1) has to be the actual torque. This is related to the ideal torque in Eq. 4. Combining the two equations and solving for the ideal torque, we have

$$\tau_{\text{actual}} = \tau_{\text{ideal}} - fr = I \alpha$$

$$\tau_{\text{ideal}} = I \alpha + fr .$$
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This means that if we plot the ideal torque calculated from Eq. 5 (let’s just call it \( \tau \) from here on) versus the measured angular acceleration, we would get a straight line with a slope that is the moment of inertia and a positive y-intercept that is the frictional force in the shaft times the radius of the pulley.

**Moments of Inertia Are Additive**

As with multiple masses connected and moving together as a single object, the effective moment of inertia of multiple objects rotating about the same axis is the sum of the individual moments of inertia. In particular, the moment of inertia of the ring sitting on the disk is the moment of inertia of the ring plus the moment of inertia of the disk.

**Procedure**

You need the following items:

- digital calipers
- 3-beam balance with 1-kg add-on
- computer with Science Workshop interface
- rotating platform base
- rotary motion sensor
- 9" plastic disk
- 4" steel ring

1. Click on Start> Science Workshop Experiments> First Quarter> Angular Acceleration.

2. Measure, record, and estimate the uncertainties in the following quantities:

   a. The mass of the disk \( m_{\text{disk}} \) in kg.

   b. The mass of the ring \( m_{\text{ring}} \) in kg.

Both of these masses are greater than 1 kg, the measuring limit of the standard balance. We have to use a 1 kg add-on weight which allows us to measure masses from 1 to 2 kg to the nearest 0.1 g. The actual weight of the add-on is less than 1 kg, but this is a case of the little skinny kid being able to balance out the big fat kid who is closer to the center by going way out at the end of the teeter-totter. *Add 1 kg to the readings of the scale; you do not add the actual weight of the add-on.*

   c. The diameter in mm of the middle pulley on the axle about which the string wraps \( d_{\text{string}} \), with the string wrapped around it (see Figure 1).

![Figure 1 Measuring the middle pulley diameter.](image-url)
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d. The diameter in mm of the middle pulley \(d_{\text{pulley}}\), the bare plastic part without string.

e. The diameter in mm of the circular part of the hole in the disk where the axle comes through \(d_{\text{hole}}\). (See Figure 2.)

b.

Figure 2 Measuring the diameter of the hole in the disk.

f. Since the disk has a hole in it, it’s really a big fat ring. Define the distance \(z\) as the wall thickness of this ring. Measure \(z\).

g. The inner diameter of the ring \(d_{\text{inner}}\) in mm.

h. The outer diameter of the ring \(d_{\text{outer}}\) in mm.

3. Place the disk on the center shaft of the rotating platform base, with the groove facing up. Place the ring in the groove. The first part of this experiment is to find the moment of inertia of the disk and ring combined, about the mutual axis of rotation.

Figure 3 Falling mass that rotates the disk and ring.

4. Place the string with the 50-g mass hanger over the edge of the pulley on the horizontal shaft as in Figure 3.

   a. Record the value of the total mass hanging over the edge.

   b. If necessary, rotate the disk counterclockwise to bring the top of the hanger just below the pulley.

   c. Make sure that the string is wrapped around the middle pulley only and that the ring is centered on the disk.

   d. Hold on to the disc to keep it from rotating. The mass should not be swinging.

5. Let go of the disk.
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a. It should start spinning in a \textit{clockwise direction}, as viewed from the top.

b. If it is spinning counterclockwise, you wound the string in the wrong direction around the pulley. If this is the case, let the mass fall all the way to the bottom and allow the disk to keep spinning so that it winds the string in the correct direction.

6. Click on the Start button at the top of the DataStudio window.

a. This DataStudio program takes five data points a second. It includes a plot of angular velocity vs. time as the mass falls. This should be a straight line with a positive slope (going up).

i. If the line is going down, your rotating object is spinning counterclockwise. See 5.b.

b. In addition to the plot, there are four digital displays that show the following:

i. The last measured value of the angular acceleration. (We ignore this number but it is needed so that the other numbers will display.)

ii. A running average of these angular accelerations for a particular run.

iii. The standard deviation of these values.

iv. The number of measurements.

c. Click on the Stop button then grab the disk to stop its rotation, \textit{before the weight hits the floor}.

7. Record the run number, the mean and the standard deviation of the angular acceleration, and the number of trials.

8. Repeat steps 4 – 7 for the following masses in g: 60, 70, 80, 90, 100, 110, 120, 130, 140, & 150. This gives you at least 11 mass-angular acceleration pairs.

9. Remove the ring. Repeat steps 4 – 8 to determine the moment of inertia of the disk alone. Because of the limited data buffer, you may have to delete some runs in DataStudio.

10. Minimize the DataStudio window. You may need to refer to the raw data, despite what you may have written down.

11. Close DataStudio at the end of class. Don’t save the activity.

\textbf{Analysis}

You need to propagate the uncertainties in these values:

- \( r_{\text{inner}} \)
- \( r_{\text{disk}} \)
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- $\tau_{\text{ideal}}$ (assume ($g-r\alpha$) is constant)
- $I_{\text{ring}}$

1. Click on Excel Templates > First Quarter > Angular Acceleration.

2. Save the empty template with the standard file name.

3. Enter in all of your data and uncertainties into the shaded cells.

4. Calculate the following radii in meters:
   a. The effective radius for the torque provided by the falling mass.
   b. The radius of the disk.
   c. The inner radius of the ring.
   d. The outer radius of the ring.

5. Propagate the uncertainties of the calculations in steps 4.b through 4.d.

6. Calculate these uncertainties. Use the standard error of $d_{\text{string}}$ and $d_{\text{pulley}}$ to find $u\{r\}$.

7. Enter in the appropriate Excel formulas for the masses that went over the edge (unit conversion) and the torques (using Eq. (5)).
   a. Use units of N·m.
   b. Use the scientific number format.

8. Calculate the standard error $u\{\alpha\}$ for each mass.

9. A good approximation to the uncertainty in the torque is $u\{\tau\} = \tau \cdot u\{r\}/r$. Calculate this in the appropriate column.

10. The plots of torque vs. angular acceleration for both objects are automatically drawn on the same graph, with trendlines and error bars. You need to include the equations.

11. Calculate the theoretical moments of inertia of the two objects (the disk and the ring) and their sum.
   a. The disk has a hole in it, so it’s really a fat ring. Use the ring formula to find its moment of inertia.
   b. Propagate the errors of these three values then calculate them.
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12. For the experimental moments of inertia, do a least squares fit with errors for both sets of data (τ vs. α). Format the slope and its error so that there is only one significant digit in the error and the two quantities have the same number of decimal places.

13. Compare the experimental values with their theoretical counterparts of the moments of inertia of the disk and the ring.

14. Report the values in your experiment of the frictional force in gram-weights retarding the disk and ring and the frictional force in gram-weights retarding the disk alone.

15. In the Systematic Error section of your Error Analysis, be sure to comment on how taking these things into account would change your results:
   a. The groove in the disk.
   b. The metal axis and the pulley fixture that also rotated.

Questions

1. A ramp is placed on a table top so that the bottom is hanging over the edge. A marble and a golf ball are released from rest at the same time on the ramp, at the same height. (The contact point for each is at the same height.) Assuming they roll straight down the ramp without slipping, following parallel paths, which reaches the bottom first? Or do they both reach the bottom at the same time? Why?

2. A filled cylindrical can and an empty can the same size are released from rest on the same ramp at the same height. Assuming they roll straight down the ramp without slipping, following parallel paths, which reaches the bottom first? Or do they both reach the bottom at the same time? Why?
Lab Report Guidelines

Lab Report Information

In this lab class you will be expected to write and submit a lab report for each experiment you perform (8 in total). Please review the following information. If anything is not clear please ask your TA:

- Lab Reports are due 6 days after the beginning of your lab class. For example, if your lab begins at 10:30 am on Wednesdays, then your lab report will be due by 10:29 am on Tuesdays.

- Submit your lab report through the proper channel for that experiment on blackboard.

- Make sure to complete each section listed on the lab report template, don’t leave any section blank.
  
  - Follow the lab report guidelines on what to include in each section. If you have any questions on what to include, talk with your TA.

  - Remember this is a report, so please use complete sentences, proper grammar and terminology and always check for spelling errors.

- A template will be provided for each lab report, but in general the report will be graded on how well you can communicate:
  
  - Experimental design including purpose of the experiment and equipment used.

  - Details of observations and measurements
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- Details of data analysis including graphs, fitting data to a line or curve, extrapolations and interpolations from the data, and so on.

- Error analysis with sources of error identified along with ways to reduce error in addition to an estimate of the magnitude and direction of errors.

- A discussion of inferences (logical conclusions) drawn from the experimental data with suggestions for ways to improve the experiment.

**Lab Report Guidelines**

The point distribution in each subcategory listed below is approximate. We use a grading rubric to grade you lab reports. The rubric is a breakdown of how well each section has been written. See the separate Grading Rubric on Blackboard.

**Abstract**

An abstract should be brief and be approximately 5-6 sentences long in paragraph form. Use the following as a checklist for your abstract:

- **Approach (1 point):** *How did you go about solving* the research question? Give a brief statement on your test design – was there a particular method, model or analysis that you used?

- **Results (2 points):** *What's the answer?* Put the result here in the form of numbers, uncertainties and units. For example if a force is measured, this would be communicated like: “The net vector force of the four forces acting on the system in equilibrium is 1.4 ± 0.5 N.” Avoid vague language such as "very", "small", or "significant."

- **Conclusions (1 point):** *What are the implications* of your answer? Did your test design support or confirm your research question or hypothesis? Don’t go into explanation here – that will be done later in the report.
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Introduction

In this section you want to give an overview.

- What are you testing?
  - Include the basic physics concepts being investigated in the experiment (don’t just rewrite the background information directly into this section).
- State your research question (or hypothesis).
- The background often includes theoretical predictions for what the results should be. If so, include this here as well as your own predictions for the experiment.

Research Design / Methods

Explain here what experimental design you used to address the research question you came up with during the discussion.

- Include the following:
  - What variables did you measure (independent and dependent)?
  - For which variables did you control?
  - What assumptions did you make with the equipment, design or theory?
  - What constraints were present in the experiment?
- Discuss any specific calculations or graphs you used to show your results or confirm your results.

Experimental Results

- You should summarize and clearly communicate results in this section. Include the following when appropriate:
  - numerical results, using appropriate decimal places (usually 1 or 2)
  - uncertainties
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- units

- When presenting the data, you should:
  - Display numerical values and units in tabular form
  - Display data graphically (clearly labeled)
    - Show fit lines (trendlines) to data points in graphs

- Discussion of each of the following is highly recommended:
  - Observations you made during the experiment
  - Any trends or patterns in the data or results
  - Relationship of any graphed data – was it linear, parabolic, exponential, no relation?
  - Reasons for outliers in your data

Discussion and Conclusions

- Restate the research question or hypothesis
  - If your group made a prediction (a statement of how you will demonstrate that your hypothesis is true), state your prediction and discuss how you came to this conclusion.

- Were the results what you expected?
  - Were your questions supported or refuted? Explain.
  - Discuss what you compared, in words without referencing SET. How did these variables compare?
  - Do the results make sense to you?

- When you are asked to analyze the uncertainties or errors in the experiment, you should:
  - Identify the sources of the error and how they affect the experiment
  - Estimate the magnitude (value) and direction of the errors, as appropriate
  - Determine the correct significant digits
  - Identify ways to reduce the error

- What inferences (logical conclusions) can you make from the experimental data?
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- How did assumptions affect your results? (An assumption is something taken for granted or accepted as true without proof.)
- How could your design be improved – consider equipment, setting, assumptions.
  - Propose questions for future studies for this experiment

**Questions**

There are two questions at the end of each experiment write-up for you to answer.

- Make sure to rewrite the questions on the lab report
- When answering the questions
  - Take into account the experiment you just did and apply those physics concepts to the situation.
  - Justify your answers - how did you come up with the answer.
  - If asked for a numerical value, show your calculations (values, units, uncertainties, as appropriate).
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Appendix G

SR-Focused Grading Rubric (second study)

<table>
<thead>
<tr>
<th>Lab Report Scoring Rubric</th>
<th>Name</th>
<th>Name</th>
<th>Date</th>
<th>Score (0-3)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td></td>
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<tr>
<td>Is able to write a brief statement summarizing how you tested your research question.</td>
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<tr>
<td>Is able to write a brief statement including the final numerical results (and units) and the comparison</td>
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<tr>
<td>Introduction</td>
<td></td>
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<tr>
<td>Is able to identify the physics used in the experiment</td>
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<tr>
<td>Is able to identify the research question (or hypothesis) to be tested</td>
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<tr>
<td>Experimental Design and Methods</td>
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<tr>
<td>Is able to design a reliable experiment that tests the hypothesis</td>
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<tr>
<td>Is able to decide parameters to be measured and identify independent and dependent variables</td>
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<tr>
<td>Is able to make use of control variables</td>
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<tr>
<td>Is able to identify assumptions that may affect the results</td>
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<tr>
<td>Is able to communicate the details of procedure clearly and completely</td>
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<tr>
<td>Results</td>
<td></td>
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<tr>
<td>Is able to record and present data in a meaningful way via data tables</td>
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<tr>
<td>Is able to present data in a meaningful way via graphs (if applicable)</td>
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<tr>
<td>Is able to identify a pattern (or lack of pattern) in the data</td>
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<tr>
<td>Discussion and Conclusions</td>
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<tr>
<td>Is able to restate hypothesis with appropriate prediction</td>
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<tr>
<td>Is able to make a reasonable claim whether hypothesis was supported or refuted</td>
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<tr>
<td>Is able to provide experimental evidence that supports claim</td>
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<tr>
<td>Is able to identify and discuss any comparisons of results with a given or known value (if applicable)</td>
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<tr>
<td>Is able to identify errors (systematic and random)</td>
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<tr>
<td>Is able to determine the way in which assumptions and errors might impact results</td>
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<tr>
<td>Is able to identify short-comings in experimental design and suggest specific improvements</td>
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<tr>
<td>Questions</td>
<td></td>
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<tr>
<td>Is able to answer questions with justification</td>
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<tr>
<td>Is able to include equations, calculations and final answer with units (as applicable)</td>
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<tr>
<td>Grammatical Considerations</td>
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<tr>
<td>Is able to include appropriate header information</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Able to use proper spelling, grammar, and punctuation</td>
<td></td>
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</tr>
</tbody>
</table>

Grade: 69- = (raw score) x 100 (promptness) =
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Appendix H
Scoring Rubrics used for Assessment

Rubric used to Assess IVs, DVs and COVs

<table>
<thead>
<tr>
<th>Identification of IV / DV</th>
<th>Control of Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None or Incorrect*</td>
</tr>
<tr>
<td>Correct</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>*Incorrect type noted as:</td>
<td></td>
</tr>
<tr>
<td>- confused with IV</td>
<td>2</td>
</tr>
<tr>
<td>- confused with DV</td>
<td></td>
</tr>
<tr>
<td>- confused with COV</td>
<td></td>
</tr>
</tbody>
</table>
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Rubric used to Assess Hypothesis, Prediction and Assumptions

From Eugenia Etkina’s ISLE Testing Experiment Rubric (Etkina, 2006)

<table>
<thead>
<tr>
<th>Ability to design and conduct a testing experiment (testing an idea/hypothesis/explanation or mathematical relation)</th>
<th>Scientific Ability</th>
<th>Missing</th>
<th>Inadequate</th>
<th>Needs some improvement</th>
<th>Adequate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Is able to identify the hypothesis to be tested</td>
<td>No mention is made of a hypothesis.</td>
<td>An attempt is made to identify the hypothesis to be tested but is described in a confusing manner.</td>
<td>The hypothesis to be tested is described but there are minor omissions or vague details.</td>
<td>The hypothesis is clearly stated.</td>
<td></td>
</tr>
<tr>
<td>2 Is able to design a reliable experiment that tests the hypothesis</td>
<td>The experiment does not test the hypothesis.</td>
<td>The experiment tests the hypothesis, but due to the nature of the design it is likely the data will lead to an incorrect judgment.</td>
<td>The experiment tests the hypothesis, but due to the nature of the design there is a moderate chance the data will lead to an inconclusive judgment.</td>
<td>The experiment tests the hypothesis and has a high likelihood of producing data that will lead to a conclusive judgment.</td>
<td></td>
</tr>
<tr>
<td>3 Is able to distinguish between a hypothesis and a prediction</td>
<td>No prediction is made. The experiment is not treated as a testing experiment.</td>
<td>A prediction is made but it is identical to the hypothesis.</td>
<td>A prediction is made and is distinct from the hypothesis but does not describe the outcome of the designed experiment.</td>
<td>A prediction is made, is distinct from the hypothesis, and describes the outcome of the designed experiment</td>
<td></td>
</tr>
<tr>
<td>4 Is able to make a reasonable prediction based on a hypothesis</td>
<td>No attempt to make a prediction is made.</td>
<td>A prediction is made that is distinct from the hypothesis but is not based on it.</td>
<td>A prediction is made that follows from the hypothesis but does not incorporate assumptions</td>
<td>A correct prediction is made that follows from the hypothesis and incorporates assumptions.</td>
<td></td>
</tr>
<tr>
<td>5 Is able to identify the assumptions made in making the prediction</td>
<td>No attempt is made to identify any assumptions.</td>
<td>An attempt is made to identify assumptions, but the assumptions are irrelevant or are confused with</td>
<td>Relevant assumptions are identified but are not significant for making the prediction.</td>
<td>All assumptions are correctly identified.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Is able to determine specifically the way in which assumptions might affect the prediction</td>
<td>No attempt is made to determine the effects of assumptions.</td>
<td>The effects of assumptions are mentioned but are described vaguely.</td>
<td>The effects of assumptions are determined, but no attempt is made to validate them.</td>
<td>The effects of the assumptions are determined and the assumptions are validated.</td>
</tr>
<tr>
<td>---</td>
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</tr>
<tr>
<td>7</td>
<td>Is able to decide whether the prediction and the outcome agree/disagree</td>
<td>No mention of whether the prediction and outcome agree/disagree.</td>
<td>A decision about the agreement/disagreement is made but is not consistent with the outcome of the experiment.</td>
<td>A reasonable decision about the agreement/disagreement is made but experimental uncertainty is not taken into account.</td>
<td>A reasonable decision about the agreement/disagreement is made and experimental uncertainty is taken into account.</td>
</tr>
<tr>
<td>8</td>
<td>Is able to make a reasonable judgment about the hypothesis</td>
<td>No judgment is made about the hypothesis.</td>
<td>A judgment is made but is not consistent with the outcome of the experiment.</td>
<td>A judgment is made and is consistent with the outcome of the experiment but assumptions are not taken into account.</td>
<td>A reasonable judgment is made and assumptions are taken into account.</td>
</tr>
<tr>
<td>9</td>
<td>Is able to revise the hypothesis when necessary</td>
<td>A revision is necessary but none is made.</td>
<td>A revision is made but the new hypothesis is not consistent with the results of the experiment.</td>
<td>A revision is made and is consistent with the results of the experiment but other relevant evidence is not taken into account.</td>
<td>A revision is made and is consistent with all relevant evidence.</td>
</tr>
</tbody>
</table>

**Rubric C**
Rubric for Argumentation Assessment

This rubric is a combination of the NSTA Sampson Rubric for argumentation (Sampson, 2004) and two categories from Eugenia Etkina’s ISLE Data Analysis Rubric (Etkina, 2006).

<table>
<thead>
<tr>
<th>Specific Ability</th>
<th>Missing</th>
<th>Inadequate</th>
<th>Needs some improvement</th>
<th>Adequate</th>
<th>ISLE Data Analysis Rubric 2007 (#1)</th>
<th>ISLE Application Experiment Rubric 2007 (#6)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to identify sources of experimental uncertainty</strong></td>
<td>No attempt is made to identify experimental uncertainties</td>
<td>An attempt is made to identify experimental uncertainties, but most are missing, described vaguely or incorrect</td>
<td>Most experimental uncertainties are correctly identified</td>
<td>All experimental uncertainties are correctly identified</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Is able to identify the shortcomings in an experimental design and suggest specific improvement</strong></td>
<td>No attempt is made to identify any shortcomings of the experimental design</td>
<td>An attempt is made to identify shortcomings, but they are described vaguely and no specific suggestions for improvements are made</td>
<td>Some shortcomings are identified and some improvements are suggested, but not all aspects of the design are considered</td>
<td>All major shortcomings of the experiment are identified and specific suggestions for improvement are made</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sufficient Claim</strong></td>
<td>No attempt is made to make a claim</td>
<td>A claim is included but it does not answer the research question</td>
<td>The claim provides a basic answer to the research question but does not explain everything</td>
<td>the claim answers the research question and explains everything it should</td>
<td>Sampson Rubric, The argument (#1)</td>
<td></td>
</tr>
<tr>
<td><strong>Accurate claim</strong></td>
<td>No attempt is made to make a claim</td>
<td>The claim is completely inaccurate</td>
<td>The claim includes some inaccurate parts of contradictions</td>
<td>The claim is completely accurate</td>
<td>Sampson Rubric, The argument (#2)</td>
<td></td>
</tr>
<tr>
<td><strong>Genuine evidence</strong></td>
<td>No attempt is made to include genuine</td>
<td>Inferences are used to support the conclusion</td>
<td>The conclusion is supported by data or observation but this information is not used to</td>
<td>Data that shows a difference between</td>
<td>Sampson Rubric, The argument</td>
<td></td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Evidence</th>
<th>Sufficient evidence</th>
<th>Adequate rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>(no data or other observations are included)</td>
<td>show a difference between groups, a trend over time, or a relationship between variables</td>
<td>groups, a trend over time, or a relationship between variables is used to support the conclusion</td>
</tr>
<tr>
<td>No attempt is made to provide sufficient evidence</td>
<td>Only a single piece of genuine evidence is used to support the conclusion</td>
<td>Includes multiple pieces of genuine evidence but not enough to support conclusion overall or each aspect of the conclusion</td>
</tr>
<tr>
<td>Includes enough genuine evidence to support the overall conclusion or each aspect of the conclusion</td>
<td>Explains why the evidence was included or how the evidence supports the claim but not both</td>
<td>Explains why the evidence was included and how the evidence supports the claim</td>
</tr>
</tbody>
</table>

Sampson Rubric, The argument (#3)

Sampson Rubric, The argument (#4)

Sampson Rubric, The argument (#5)
Appendix I

Student Survey

1. Did you take physics as a junior or senior in high school?
   Yes  No
   If yes, how well did it prepare you for the lecture class?
   Very Well  Ok  Not at All

2. What is the highest level math course you have taken?

3. What other science laboratory classes have you taken/currently taking in college?

4. What aspects of the lab were particularly useful in preparing you for lecture?

5. What aspects of the lab could have used improvement in preparing you for lecture?

6. Were you successful in your laboratory class? Please indicate why you think this was so.

7. What part of your participation in lab class would you consider to be the highlight or what went well that should be continued in the future?

   The low points or what did not go very well or was confusing and should be updated for future lab?

8. How many labs did you miss?
   0  1  2  3  4+

9. Did you ask for help from your TA during lab?
   Yes  No
   If yes, how did your TA respond?
   (or other ______________________)
   Just gave me the answer  Asked me questions  Didn’t help

10. Physics lab helped me understand lectures better.
    1 helped  2  3 mid  4  5 No help

11. Physics lab helped me prepare for recitations
    1 helped  2  3 mid  4  5 No help

12. Physics lab gave me feedback on what I knew and didn’t know
    1 yes  2  3 some  4  5 no

13. Physics lab helped me think more deeply about course materials
    1 helped  2  3 mid  4  5 No help

14. I learned new physics concepts in physics labs
    1 yes  2  3 some  4  5 no

15. I prefer a physics lab that requires me to extend my thinking
    1 high  2  3 mid  4  5 low

16. I prefer a physics lab that requires me to do problem solving.
    1 high  2  3 mid  4  5 low

17. I prefer a physics lab with detailed, step-by-step instructions
    1 high  2  3 mid  4  5 low

18. What day and time was your lab class (please circle)?
    Mon  Tue  Wed  Thur
    AM:  8  8:30  9  9:30  10:30  11
    PM:  1  1:30  3  3:30  4  4:30  5:30  6

19. What is your intended major?

20. What is your grade level?
    Fr  So  Jr  Sr  Sr+
Appendix J

Questions for Teaching Assistant Interviews

1. How well did students work in groups of four?
2. How well did the student groups come up with a design for the lab?
3. Was student participation in the labs better/worse/same as compared with the regular labs? Explain.
4. Do you think the focus of the lab reports gave students better scientific reasoning skills?
5. Do you think the alternative teaching style gave students better scientific reasoning skills?
6. Do you think the focus of the lab reports gave students better problem solving skills?
7. Do you think the alternative teaching style gave students better problem solving skills?
8. In your opinion, did the scaffolding help the students retain knowledge from the previous labs? By scaffolding, I mean: starting with more detailed information and charts in the first few labs and less detail and no charts in the later labs; and, more prompts at the beginning and fewer prompts at the end.
9. How did teaching the alternative labs compare with the regular labs?
10. How well did switching between whole class discussions and group processes work?
11. Was the use of prompts helpful to the flow of the lab?
12. Was the use of prompts helpful to students’ learning?
13. On average, how much preparation time did you need before each lab? Was it more or less time than the regular labs?
14. How did grading the lab reports compare with the regular lab reports?