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Using Physics to Help Students Develop Scientific Habits of Mind

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Abstract

Interactive engagement curricula are successful in helping students develop conceptual understanding of physics principles and solve problems. However, another benefit of actively engaging students in the construction of their physics knowledge is providing them with an opportunity to engage in habitual "thinking like physicists". Some examples of such thinking are: drawing a sketch before solving any physics problem, subjecting normative statements to experimental testing, evaluating assumptions, or treating each experimental results as an interval. We can help students develop these "habits of mind" if we purposefully and systematically engage them in the processes that mirror the processes in which physicists engage when they construct and apply knowledge. For such engagement to occur, we need to deeply re-conceptualize the role of experiments in physics instruction and their interaction with the theory. However, most importantly, we need to rethink the role of the instructor in the classroom.

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1 Introduction

What knowledge and what abilities are needed to succeed in this 21st century workplace? This question has been addressed by individual research studies examining the need for various process abilities and for declarative knowledge of people in that workplace (Chin, et.al., 2004; Coles, 1997; Gott, et.al., 1999; Lottero-Perdue, et.al., 2002). Duggan and Gott (2002: p. 756–782) studied the science used by employees in five science-based industries: a chemical plant specializing in cosmetics and pharmaceuticals, a biotechnology firm specializing in medical diagnostic kits, an environmental analysis lab, an engineering company manufacturing pumps for the petrochemical industry, and an arable farm. They found that most of the scientific conceptual understanding used by employees was learned on the job, and not in high school or university courses. They concluded: "A secure knowledge of procedural understanding appeared to be critical."

Aikenhead (2005: p. 242–275) summarized his own and other studies as follows: "In science-rich workplaces, procedural knowledge had a greater credence than declarative knowledge (Chin, et.al. 2004) and employees consistently used concepts of evidence in their work to such an extent that Duggan and Gott (2002) concluded: procedural knowledge generally, and concepts of evidence specifically, lie at the heart of... science-based occupations."

In addition to individual research studies like these, there have been a plethora of national studies and reports concerning desired outcomes of science education (Czujko, 1997[1]; Improving Undergraduate Instruction in Science, Technology, Engineering, and Mathematics: Report of a Workshop, 2003; Educating the Engineer of 2020: Adapting Engineering Education to the New Century, 2005). Recently published Next Generation Science Standards (2013) used the term "science practices" and made those as important for student learning as the content of science itself. In this paper I will use the term "scientific abilities" coined and used by the Physics Education Research group at Rutgers University to describe our work and findings in this area.

2 Scientific abilities

We started the scientific abilities project started in 2003 by identifying the most important procedures, processes, and methods that scientists use when constructing knowledge and when solving experimental problems. The list of scientific abilities that our physics education research group developed includes (A) the ability to represent physical processes in multiple ways; (B) the ability to devise and test a qualitative explanation or quantitative relationship; (C) the ability to modify a

[1] Updated standards are available at http://www.abet.org/accreditation-criteria-policies-documents/.

qualitative explanation or quantitative relationship; (D) the ability to design an experimental investigation to develop a new concept, test a concept or apply a set of concepts to solve a practical problem; (E) the ability to collect and analyze data; (F) the ability to evaluate experimental predictions and outcomes, conceptual claims, problem solutions, and models, and (G) the ability to communicate.

To help students develop these abilities, one needs to engage students in appropriate activities, and to find ways to assess students' performance on these tasks and to provide timely feedback. Activities that incorporate feedback to the students are called formative assessment activities. Specifically, the students need to understand the target concept or ability that they are expected to acquire and the criteria for good work relative to that concept or ability. They need to be able to assess their own efforts in light of the criteria. Finally, they need to share responsibility for taking action in light of the feedback. The feedback should be descriptive and criterion-based as opposed to grades without clear criteria.

In real life, how can one make formative assessment and self-assessment possible?

One way to implement formative assessment and self-assessment is to use self-assessment rubrics. An assessment rubric allows learners to see learning and performance goals, self-assess their work, and modify it to achieve the goals. A rubric contains descriptions of different levels of performance, including the target level. Students can use the rubric to help self-assess and improve their own work. Instructors can use the rubric to evaluate students' work and to provide feedback.

After making the list of scientific abilities that we created rubrics to help students self-assess themselves and improve their work. The process through which we developed and validated the rubric is described in detail in (Etkina & Van Heuvelen, et.al., 2006). The most important part of the work was that we found that it is impossible to assess each ability from the list above as one unit. For the purposes of development and assessment we had to break each ability into smaller sub-abilities (total of 39 items). For example, for the ability to collect and analyze data we identified the following sub-abilities: (i) the ability to identify sources of experimental uncertainty, (ii) the ability to evaluate how experimental uncertainties might affect the data, (iii) the ability to minimize experimental uncertainty, (iv) the ability to record and represent data in a meaningful way, and (v) the ability to analyze data appropriately. Figures 1 and 2 below shows examples of several rubrics (all of them are available at http://paer.rtugers.edu/scientificabilities).

Figure 1 shows rubrics for several sub-abilities of the ability to represent information in multiple ways and Figure 2 shows rubrics several sub-abilities of the ability to design experimental investigation. Each item in the rubrics corresponds to one of the sub-abilities. The scale of 0–3 in the scoring rubrics (0, missing; 1, inadequate; 2, needs some improvement; and 3, adequate) was found to be the easiest when writing the rubrics and also later when we needed to achieve inter-rate reliability scoring student work (see examples in the Figures 1 and 2).

3 Investigative Science Learning Environment

Obviously, the rubrics alone are not enough to help the students learn to think like scientists. They need to be engaged in the activities that mirror scientific practice. Many inquiry-based curricula have individual activities that engage students in some of the practices, but there are a few which do it systematically and purposefully. One of those is Investigative Science Learning Environment (ISLE).

Ability to represent information in multiple ways				
Scientific Ability	**Missing**	**Inadequate**	**Needs some improvement**	**Adequate**
Representations students can make				
Picture	No representation is constructed.	Picture is drawn but it is incomplete with no physical quantities labeled, or important information is missing, or it contains wrong information, or coordinate axes are missing.	Picture has no incorrect information but has either no or very few labels of given quantities. Majority of key items are drawn in the picture.	Picture contains all key items with the majority of labels present. Physical quantities have appropriate subscripts
Force Diagram	No force diagram is constructed.	Force diagram is constructed but contains major errors: missing or extra forces (not matching with the interacting objects), incorrect directions of arrows or incorrect relative length of force arrows.	Force diagram contains no errors in force arrows but lacks a key feature such as labels of forces with two subscripts or forces are not drawn from single point.	The diagram contains all appropriate force and each force is labeled so that one can clearly understand what each force represents. Relative lengths of force arrows are correct.
Motion Diagram	No motion diagram is constructed.	The diagram does not represent the physical process accurately, either spacing of the dots or the directions and length of v arrows or delta v arrows do not match the motion.	The diagram matches the process but is missing one key feature: dots that represent position or velocity arrows, or delta v arrows.	The diagram contains no errors in dots, v arrows or delta v arrows and it clearly matches the motion of the object.
Mathematical	No representation is constructed.	Mathematical representation lacks the algebraic part (the student plugged the numbers right away) has the wrong concepts being applied, signs are incorrect, or progression is unclear. The first part should be applied when it is appropriate.	There are no errors in the reasoning, however they may not have fully completed steps to solve problem or one needs effort to comprehend the progression.	Mathematical representation contains no errors and it is easy to see progression from the first step to the last step. The final answer is reasonable in terms of magnitude, has correct units and is makes sense for the limiting cases.

Figure 1: Sub-abilities of the ability to represent information in multiple ways

Scientific Ability	Missing	Inadequate	Needs some improvement	Adequate
Is able to identify the phenomenon to be investigated	No mention is made of the phenomenon to be investigated.	An attempt is made to identify a phenomenon to be investigated but is described in a confusing manner, or is not the phenomena of interest	The phenomenon to be investi-gated is described but there are minor omissions or vague details.	The phenomenon to be investigated is clearly stated.
Is able to design a reliable experiment that investigates the phenomenon	The experiment does not investigate the phenomenon.	The experiment involves the phenomenon but due to the nature of the design it is likely the data will not contain any interesting patterns.	The experiment investigates the phenomenon and it is likely the data will contain interesting patterns, but due to the nature of the design some features of the patterns will not be observable.	The experiment investigates the phenomenon and there is a high likelihood the data will contain interesting patterns. All features of the patterns have a high likelihood of being observable.
Is able to decide what is to be measured and identify independent and dependent variables	The chosen measure-ments will not produce data that can be used to achieve the goals of the experiment.	The chosen measurements will produce data that can be used at best to partially achieve the goals of the experiment.	The chosen measurements will produce data that can be used to achieve the goals of the experiment. However, independent and dependent variables are not clearly distinguished.	The chosen measurements will produce data that can be used to achieve the goals of the experiment. Independent and dependent variables are clearly distinguished.
Is able to use available equipment to make measu-rements	At least one of the chosen measure-ments cannot be made with the available equipment.	All chosen measurements can be made, but no details are given about how it is done.	All chosen measurements can be made, but the details of how it is done are vague or incomplete.	All chosen measurements can be made and all details of how it is done are clearly provided.
Is able to describe what is observed without trying to explain, both in words and by means of a picture of the experimental set-up.	No description is mentioned.	A description is mentioned but it is incomplete. No picture is present. Or, most of the observations are mentioned in the context of prior knowledge.	A description exists, but it is mixed up with explanations or other elements of the experiment. A labeled picture is present. Or some observations are mentioned in the context of prior knowledge.	Clearly describes what happens in the experiments both verbally and by means of a labeled picture.

Figure 2: Rubrics for several sub-abilities of the ability to design an experiment to investigate a phenomenon

ISLE (Etkina & Van Heuvelen, 2007) (developed in 1985–2000 first for high school physics and then for college physics) engages students in the processes that mirror scientific practice to help them learn physics. Specifically, students start learning a new concept by observing a few very simple experiments (called observational-experiments). They then use available representations (motion diagrams, graphs, force diagrams, energy bar charts, etc.) to identify patterns, develop multiple explanations for those patterns and finally, test the explanations (with the purpose of ruling them out). The testing involves first designing a new experiment, the outcome of which they can predict using their explanation, second conducting the experiment, and third comparing the predictions to the outcomes of the testing experiment. This purposeful testing of proposed explanations using hypothetico-deductive reasoning is one of the most important features of ISLE, which in turn directly reflects common reasoning in science and, in particular, in experimental physics. Often the unexpected outcome of a testing experiment serves as an observational experiment for a new cycle.

The ISLE framework was developed to help students construct new concepts (Etkina & Van Heuvelen, 2007), however it can be successfully utilized when students apply the concepts that they have already constructed to analyze complex phenomena (Etkina, Planinšič & Vollmer, 2013). Recently and introductory physics textbook using ISLE approach with the supporting workbook for the students and an instructor guide for the teachers has been published (Etkina, Gentile & Van Heuvelen, 2013a; Etkina, Gentile & Van Heuvelen, 2013b; Etkina, Brookes & Van Heuvelen, 2013).

4 Developing Scientific Abilities in an ISLE-based course

Over the last 10 years we conducted multiple studies investigating how introductory students develop scientific abilities in an ISLE-based course in which most of the activities (including instructional labs where the students design their own experiments using scientific abilities rubrics) engage students in the processes that mirror scientific practice. In this section I will present brief summaries of those studies with relevant references so the reader can find the original papers and explore the details. Numerous examples of the activities that students do, including all laboratory investigations can be found at http://paer.rutgers.edu/scietificabilities.

4.1 Study of multiple representations

This study is reported in the paper by Rosengrant, Van Heuvelen and Etkina (2009). The study investigated how students who learned physics through ISLE with an explicit focus on representing phenomena in multiple ways use those representations when they are solving problems on their own (an explicit focus involves several things: teaching students to construct a mathematical representation of the problem using one of the concrete representations; asking them to represent the problem situation without solving for anything and engaging them in Jeopardy-type problem where the solution is provided and the students need to recreate the problem situation and represent it in multiple ways; all of those multiple representation activities are provided in reference 15 and two examples are in Appendix 1 in this paper). Specifically, the study investigated the use of free-body (force) diagrams by students in a large enrollment (700 students) algebra-based general physics course. It was a two-year quantitative and qualitative study of students' use of free-body diagrams while solving physics problems. We found that when students are in a course that consistently emphasizes the use of free-body diagrams in the context of ISLE, the majority of them (60–70 % as opposed to 15 % in a traditionally taught course) do use diagrams on their own to help solve exam problems even when they receive no credit for drawing the diagrams (to make this conclusion we collected scrap papers on which student did work solving problems on multiple choice exams, we identified those students who drew the diagrams, and then we scored those free-body/force diagrams using the rubrics described above). We also found that students who draw diagrams correctly (scored a 2 and 3 on the free-body/force diagram rubric) are significantly more successful in obtaining the right answer for the problem. Lastly, we interviewed students to uncover their reasons for using free-body diagrams. We found that high achieving students used the diagrams to help solve the problems and as a tool to evaluate their work while low achieving students only use representations as aids in the problem-solving process. (See reference 16 for the details of the study).

4.2 Study of student acquisition of scientific abilities

We conducted several studies that investigated how students develop experiment-related scientific abilities in real time in ISLE instructional laboratories. The ISLE laboratories are naturally integrated in the learning process. In laboratories students design their own experiments without cookbook instructions but with the support of special guiding questions and self-assessment rubrics described above. An example of a laboratory handout is provided Appendix B.

The most important aspect of the ISLE laboratories is that students have to implement different scientific abilities, such as evaluating uncertainties and assumptions not because the lab handout requires those steps but because without them the students cannot solve the problem. For example, the students need to determine the specific heat of an object made of an unknown material. If they conduct only one experiment, there is no way to say whether the number they obtain makes any sense since there is no "accepted value". Therefore, the students need to design a second independent experiment and then make a decision on the value of the specific heat based on the assumptions in their mathematical procedure and the experimental uncertainties in their values.

In a typical laboratory, students conduct one or two experiments.

All of the experiments can be grouped into three big categories (according to their role in the ISLE cycle). The first type is observational experiment that takes place when students have to investigate a new phenomenon that they have not yet seen in large room meetings or problem solving sessions. When students design observational experiments, they need to figure out how to collect the data suggested by the laboratory handout and how to analyze the data to find patterns. For example, they need to find a pattern between the current through and potential difference across a resistor. The second type of experiments is testing experiment that students design when they need to test a hypothesis. This hypothesis is usually based on a pattern observed in a previous laboratory experiment or it is a hypothesis that students devised in other parts of the course prior to the laboratory. Sometimes they have to test a hypothesis that "a friend has devised" — these are usually based on known student ideas from the physics education research. For example, students need to test a hypothesis that magnetic poles are electrically charged. The third type is application experiment. This is experimental problem that requires students to design several experiments to determine the value of some physical quantity — such as the coefficient of friction between their shoe and the carpet. The application experiments, as their name suggests, are the experiments where students have to apply one or more concepts that they already know to solve the problem. The laboratory handout scaffolding questions and the rubrics are different for these three types of experiments. Appendix B shows an example of the laboratory handout for the first two types of experiments.

To study the development of abilities that students develop while designing and carrying out the above experiments abilities we collected and scored the lab reports of 60 students in an algebra-based introductory physics course at Rutgers University (enrollment of about 200 students) during one semester (the course followed ISLE). The details of the studies can be found in the following references (Etkina, Karelina & Ruibal-Villasenor, 2008; Etkina & Karelina, et.al., 2009; Karelina & Etkina, 2007). Here I provide the summary of our findings.

The research questions that we answered in the reported studies were: How long does it take for the majority of the students to develop different scientific abilities? Does this time depend on the ability? And are there any specific abilities that are especially difficult?

We investigated several abilities and their development over the course of one semester by scoring the lab reports of 60 students in the course Physics for the Sciences at Rutgers University using the rubrics described above. We found that at the beginning of the semester the majority of the students received the scores of 0 and 1 on the rubrics and as the semester progressed the scores increased. After week #5 students started showing significant improvement on some abilities (ability to design an experiment, ability to identify experimental uncertainties, ability to communicate) and by week 7–8 (this means that students had 7 to 8 3-hour laboratories and had to write 7 to 8 lab reports) over 80 % were receiving scores of 2 and 3 on the majority of the rubrics (including such ones as the ability to evaluate uncertainty, ability to recognize the difference between the hypothesis and the prediction, ability to identify assumptions, etc.). After week 8 the number of students receiving high scores stopped changing being settled around 80 %. The only ability that never reached 80 % of scores 2 and 3 and kept steadily improving was the ability to evaluate the effects of assumptions. We think that this finding can be explained by the fact that this particular ability depends on the knowledge of the relevant physics material more than any other abilities. These results have been repeated multiple times over the years and we find them to be very robust. Another robust finding (that persists in different universities) is student attitude towards such laboratories. As they differ drastically from traditional cook book labs to which students are accustomed, at the beginning of the semester they are lost and anxious, and do not know what to do or how to do it. However by about week 8 of the semester one can notice a significant shift in their behaviors. They become more relaxed and they know what is expected of them — they know what to do. The real changes come at the end of the semester when they not only know what to do but also how to do it. These three easily recognizable stages in student attitudes towards such design abs were first documented by X. Zou who implemented ISLE labs at the California State University, Chico but later we also observed them year after year at Rutgers.

4.3 Transfer of scientific abilities

After we found that students do indeed develop scientific abilities as scored by the rubrics when working on the physics design experiments we wanted to investigate whether they transfer these abilities to a different content area. The issue of transfer is extremely complicated and I will not delve here into the details of different models of transfer and how we set up the experiment to study one of the types of transfer in our case. All of the details are described in the paper by Etkina et.al, published in 2010 in the Journal of Learning Sciences (Etkina et.al., 2010). Here, again, I will briefly outline the structure of the study and summarize the findings.

Population: The study was conducted in the first (fall) semester the same course where we conducted the previous study, there were 193 students attending various activities varied through the semester. There were two 55-min lectures, one 80-min recitation, and a 3-hour lab per week. There were two midterm exams and one paper-and-pencil final exam and final lab exam. All students learned through the same ISLE approach in large room meetings and in smaller recitations. The lab sections were split into two groups: design labs (4 sections) and non-design labs (4 sections). Students registered for the sections in March of the previous academic year. In the previous years we found no difference in performance of lab sections on exams, thus we can assume that during the experimental year the student group distribution was random. During the semester, students were not informed about the study. At the end, we disclosed the procedure and students signed a consent form allowing us to use their work for research. We took precautions to ensure that the groups were equal in learning ability using Lawson's test of hypothetico-deductive reasoning in the first lab session (Lawson, 1978). Coletta and Philips (2005) found that student's learning gains are strongly correlated with their scores on this test. Our lab sections were statistically the same. To ensure that the treatment was the same too, we used the same three instructors to teach the labs. Two of the instructors taught one design and one non-design section and the third instructor taught two of each. All instructors were members of the PER group, highly skilled in the interactive teaching.

Experimental group: Design labs (4 sections): Students in the experimental group had *ISLE* design labs described above. They had to design their own experiments and use rubrics for self-assessment.

Control group: Non-design labs (4 lab sections): Students in the control group used the same equipment as in design labs and performed the same number (sometimes even more) experiments. The lab handouts guided them through the experimental procedure but not through the mathematics.

Assessment of student learning of physics and acquisition and transfer of scientific abilities: We assessed student learning by their performance three paper-and pencil course exams (2 midterms and one final) and on two transfer tasks. Course exams had a multiple-choice portion and an open-ended portion (3 problems per midterm and 5 on the final).

Transfer to Physics: To assess how students transfer scientific abilities to an unfamiliar physics content in the same functional context, we developed a lab task where both groups designed an experiment and wrote a lab report. In contrast to regular labs that students performed during semester, this particular task was identical for the experimental and the control groups. The task involved drag force in fluid dynamics. This physics content was not covered in the course. Students were provided some necessary and some redundant information in the lab handout and had access to textbooks and the Internet.

The students performed this task during the lab (3 hours) on week 13 of the semester. Prior to this, they performed 10 labs.

Transfer to Biology: The second transfer experiment involved a biology task that was given as the final lab exam for the course in week 14. Both the experimental and the control groups had to design an experiment to find the transpiration rate of a certain species of plant and subsequently to write a report detailing their experimental procedures, calculations and conclusions.

During the practical exam students in each lab section worked in the same group of three or four as they did during the semester. As during the semester, students submitted individual reports for grading.

When the exam was graded students from both groups received scores that reflected their performance relative to the standards for two different kinds of labs. After the semester was over, the researchers used the scientific abilities rubrics to code student work.

Findings Acquisition of normative science concepts

With regard to the normative science concepts that were assessed via multiple-choice and free-response exam questions and problems, students in the design and non-design groups performed similarly on both midterms and the final exam: Midterm Exam 1, $\mathbf{F}(1,182) = 0.25$, $\mathbf{p} = 0.62$; Midterm Exam 2, $\mathbf{F}(1,180) = 1.31$, $\mathbf{p} = 0.25$; final exam, $\mathbf{F}(1,180) = 0.45$, $\mathbf{p} = 0.502$ (to make three contrasts, we used the sequential Bonferroni correction, critical value of 0.017).

Scientific abilities rubrics: Physics Transfer task: Reading of the lab reports revealed the features that made a difference in the performance of two groups. The quantitative analysis of the lab reports supported the general impression on students' performance. There were significant differences in the lab reports of design students and non-design students. Design students demonstrated significantly better scientific abilities than the non-design students specifically on the following rubrics: *Evaluating the effect of assumptions* (fifty seven design students (more then 60 %) received score 2 or 3; not a single student in non-design section made an attempt to do this); *Evaluating effect of uncertainties:* (only 11 of non-design students (12 %) got score 2 or 3 while more then 50 % of design students evaluated the effect of experimental uncertainties in this lab. The difference between the groups is statistically significant (Chi-square$=$ 30, $p < 0.001$)); *Evaluating the result by means of an independent method* (about 64 of design students (72 %) got score 2 or 3, while in non-design sections only 38 students (43 %) did. The difference between the groups is statistically significant (Chi-square$=$ 16, $p < 0.001$)); *Communication* (more then 60 % of design students drew a picture while only 8 % of non-design students did. The difference in student scores on the communication is statistically significant (chi-square$=$ 60.6, $p < 0.001$)). In addition we found the differences in students use of force diagrams and overall consistency o representations with the design students significantly outperforming the non-design students.

We found very similar results for the biology task, design group students demonstrated the transfer of acquired scientific abilities significantly better than non-design students. The details of the analysis can be found in reference 18.

5 Discussion

In my talk at the conference and here I attempted to show that inquiry-based instruction with proper scaffolding and formative assessment can be successful in helping students develop scientific habits of mind that are needed for the success in the 21st century. Examples of such habits of mind — scientific abilities — are the skills and procedure that are needed in all areas of future lives of our students and are called for by the documents guiding science education. We can help all students (not necessarily physics majors) develop such abilities and later these students also transfer those abilities to new content areas. Three things are important here:

1. ISLE is not an open inquiry-based curriculum that engages student in random investigations of phenomena with the hope of them finding out things on their own. It is a heavily scaffolded approach that encourages students to construct and test their own understanding through a series of carefully chosen experimental investigations supported with specific questions and self-assessment rubrics, aided by concrete representations.
2. It takes time for the students to develop those abilities (5–8 weeks), so we should not get discouraged when after a month of instruction our students still cannot design their own experiments or evaluate how the assumptions might affect the results of their calculations.
3. We should not be afraid that students will not learn the "right" physics if they design their won experiments and make mistakes. We found that engaging students in experimental design when they sometimes come up with "wrong" solutions and do not practice solving traditional physics problems does not hurt them in terms of the acquisition of normative physics knowledge. However, they benefit significantly in terms of persistence and ability to approach new problems as scientists.

Appendix 1

Examples of Multiple Representations activities:

Representing the problem situation in multiple ways: You are riding to the top floor of your residence hall. As the elevator approaches your floor, it slows to a stop. Construct a motion diagram and a free-body (force) diagram for the elevator [with you inside] as the object of interest as the elevator slows down to a stop.

Jeopardy problem: The mathematical expressions below could represent many physical situations. Invent one situation and describe it with words, with a force diagram, with a sketch, and with a motion diagram. The object moves vertically. We assume that $g = 10\ \mathrm{m/s^2} = 10\ \mathrm{N/kg}$.

$$\begin{aligned} -T + (1\,000\ \mathrm{kg})(10\ \mathrm{N/kg}) &= (1\,000\ \mathrm{kg})(2.0\ \mathrm{m/s^2}) \\ -0 + (-8.0\ \mathrm{m/s}) &= (2.0\ \mathrm{m/s^2})t \\ y &= (-8.0\ \mathrm{m/s})t + (1/2)(2.0\ \mathrm{m/s^2})t^2 \end{aligned}$$

Appendix 2

A laboratory handout with the examples of two different types of experiments:

Lab 3: The Electric Potential and Electric Currents

LEARNING GOALS OF THE LAB

1. Learn how to construct a working apparatus using a schematic picture.
2. Learn to fit functions to data in order to represent graphical patterns with mathematical expressions.

I. OBSERVATIONAL EXPERIMENT: DETERMINE A MATHEMATICAL RELATIONSHIP BETWEEN CURRENT THROUGH AND VOLTAGE ACROSS A RESISTOR

Design an experiment to determine a mathematical relationship between the current through a resistor and the voltage across that resistor. First you will design your experiment using the simulation from experiment II. Clear the simulation; then use it to build a circuit that will allow you to accomplish your goal.

To measure the current through the resistor using an ammeter, you need to let this current pass **through the ammeter**. To measure the voltage (potential difference) across the resistor using a voltmeter, you need to connect the voltmeter so **it measures the electric potential before and after the resistor**:

An ammeter and a voltmeter are available in the simulation by checking the appropriate checkboxes. Once you have built the circuit using the simulation, call your TA over and explain it to them. Also, explain what measurements you are going to make and how you will use them to accomplish your goal. Once you have done this, build your circuit using real equipment.

Available equipment: Voltage source resistor, 2 multimeters, connecting wires.

RUBRIC B: Ability to design and conduct an observational experiment

Scientific Ability		Missing	Inadequate	Needs some improvement	Adequate
B3	Is able to decide what physical quantities are to be measured and identify independent and dependent variables	The physical quantities are irrelevant.	Only some of the physical quantities are relevant.	The physical quantities are relevant. However, independent and dependent variables are not identified.	The physical quantities are relevant and independent and dependent variables are identified.
B7	Is able to identify a pattern in the data	No attempt is made to search for a pattern	The pattern described is irrelevant or inconsistent with the data	The pattern has minor errors or omissions	The patterns represents the relevant trend in the data

RUBRIC G: Ability to collect and analyze experimental data				
Scientific Ability	Missing	Inadequate	Needs some improvement	Adequate
G2 Is able to evaluate specifically how identified experimental uncertainties may affect the result	No attempt is made to evaluate experimental uncertainties.	An attempt is made to evaluate experimental uncertainties, but most are missing, described vaguely, or incorrect. Or only absolute uncertainties are mentioned. Or the final result does not take the uncertainty into the account.	The final result does take the identified uncertainties into account but is not correctly evaluated.	The experimental uncertainty of the final result is correctly evaluated.
G4 Is able to record and represent data in a meaningful way	Data are either absent or incomprehensible.	Some important data are absent or incomprehensible.	All important data are present, but recorded in a way that requires some effort to comprehend.	All important data are present, organized, and recorded clearly.
G5 Is able to analyze data appropriately	No attempt is made to analyze the data.	An attempt is made to analyze the data, but it is either seriously flawed or inappropriate.	The analysis is appropriate but it contains minor errors or omissions.	The analysis is appropriate, complete, and correct.

Include the following in your writeup:

a) Devise a procedure for your investigation and briefly describe your experimental design. Include a labeled sketch of your setup.

b) What important physical quantities change during the experiment? What are the independent and dependent variables in your experiment?

c) Build the circuit according to your picture. **Then, call your lab instructor over to check the circuit.** After you've done that, you can turn on the voltage source.

d) Record your data in an appropriate manner. Construct a graph. Think what mathematical functions may fit you data (Excel has features that let you explore how well different functions fit your data).

e) Find the SIMPLEST mathematical function that does fit your data. Think of uncertainties (error bars). Does the function you chose cross through the regions defined by the error bars?

f) Formulate a quantitative rule relating the current through a resistor to the voltage (potential difference) across the resistor.

II. TESTING EXPERIMENT: CURRENT-VOLTAGE DEPENDENCE

The goal of this experiment is to test whether the rule relating the current through a resistor and the voltage across resistor is applicable to a light bulb. Remember that the purpose of testing experiment is to reject, not to support the rule under test.

Available equipment: Voltage source (again, keep the voltage below 5 V), light bulb, resistors, 2 multimeters, connecting wires.

Write the following in your report:

a) State what rule you are testing.
b) Brainstorm the task and make a list of possible experiments whose outcome can be predicted with the help of the rule.
c) Briefly describe your chosen design. Include a labeled sketch.
d) **Use the rule being tested to make a prediction** about the outcome of the experiment.
e) Perform the experiment. Record the outcome.
f) Is the outcome consistent or inconsistent with the prediction? Explain in detail how you decided this.
g) Based on the prediction and the outcome of the experiment, what is your judgment about the rule being tested?
h) Ask your classmates in other lab groups about their results. Are they consistent with yours?

V. WHY DID WE DO THIS LAB?

a) Discuss how plotting the data in experiment III helped you identify the relationship between the current through the resistor and the voltage across it.
b) What other question/phenomena could you investigate using the available equipment from this lab?
c) Give an example of an experiment from your field of study where a pattern in data is used to construct a mathematical relationship.

POSTSCRIPT (OPTIONAL, AND REALLY JUST FOR YOUR AMUSEMENT): THE PLATYPUS

The platypus, a native of Australia, is an odd type of mammal called a monotreme. It has fur, webbed feet, and a bill like a duck. The young are born from eggs and although the mother produces milk for them she has no nursing organs we would recognize: milk seeps through a patch of skin on the mother's underside.

The platypus lives in freshwater streams and eats crustaceans, insects, and small fish. The platypus is a beaver-sized animal and must need to eat a lot of bugs, but its small and beady eyes don't look very helpful for finding its prey among the rocks and sand at the bottom of a muddy creek.

The secret to this animal's success is actually in its bizarre beak. This contains millions of electroreceptive cells that can detect the incredibly minute electric field that is generated by the neurons of bugs and shrimp!

Professor Uwe Proske of Monash University reports that about two-thirds of the sensory area of a platypus's brain is connected to the beak. The system seems to have evolved completely independently from similar electroreceptive systems in fish such as sharks.

However it operates, and however it evolved, it seems to work remarkably well. The platypus manages to capture half its body weight in food every night.

References

Aikenhead, G. S. (2005). Science-Based Occupations and Science Curriculum: Concepts of Evidence. *Science Education*, 89, 242–275.

Chin, P., Munby, H., & Hutchinson, N. L., et.al. (2004). Where's the science? Understanding the form and function of workplace science. In E. Scanlon, P. Murphy, J. Thomas, & A. E. Whitelegg (Eds.), *Reconsidering science learning*, (118–134), London: Routledge Falmer.

Coles, M. (1997). What does industry want from science education? In K. Colhoun, R. Panwar, & S. Shrum (Eds.), *Proceedings of the 8th symposium of IOSTE* (292–300). Edmonton: Faculty of Education, University of Alberta.

Coletta, V. P. & Phillips, J. A. (2005). Interpreting FCI scores: Normalized gain, preinstruction scores, & scientific reasoning ability. *American Journal Physics*, 73(12), 1172–1182.

Czujko, R. (1997). The Physics Bachelors as a Passport to the Workplace: Recent Research Results in The Changing Role of Physics Departments in Modern Universities. E. F. Redish & J. S. Rigden, (Eds). *AIP Conf. Proc.* 399, Woodbury, NY.

Duggan, S. & Gott, R. (2002). What sort of science education do we really need? *International Journal of Science Education*, 24, 661–679.

Educating the Engineer of 2020: Adapting Engineering Education to the New Century, (2005). The National Academies Press, N.W., Washington. Available at http://nap.edu/catolog/11338.html

Etkina, E., Brookes, D. & Van Heuvelen, A. (2013). *Instructor Guide for College Physics.* San Francisco, CA: Pearson, 2013.

Etkina, E., Gentile, M. & Van Heuvelen, A. (2013a). *College Physics.* San Francisco, CA: Pearson.

Etkina, E., Gentile, M. & Van Heuvelen, A. (2013b). *The Physics Active Learning Guide* (2nd ed.). San Francisco, CA: Pearson.

Etkina, E., Karelina, A. & Ruibal-Villasenor, M. (2008). How long does it take? A study of student acquisition of scientific abilities. *Physical Review, Special Topics, Physics Education Research*, 4, 020108; 9.

Etkina, E. & Karelina, A., et.al. (2009). Using action research to improve learning and formative assessment to conduct research. *Physical Review. Special Topics, Physics Education Research*, 5, 010109; 14.

Etkina, E., Karelina, A. & Ruibal-Villasenor, M., et.al. (2010). Design and reflection help students develop scientific abilities: Learning in introductory physics laboratories. *Journal of the Learning Sciences*, 19, 1, 54–98.

Etkina, E., Planinšič, G. & Vollmer, M. (2013). A simple optics experiment to engage students in scientific inquiry. *American Journal of Physics*, 81 (11), 815–822.

Etkina, E., Van Heuvelen, A. & White-Brahmia, S., et.al. (2006). Developing and assessing student scientific abilities. *Physical Review. Special Topics, Physics Education Research.* 2, 020103.

Etkina, E. & Van Heuvelen, A. (2007). Investigative Science Learning Environment — A Science Process Approach to Learning Physics, in E. F. Redish, P. Cooney (Eds.), *Research Based Reform of University Physics*, (AAPT). Available at http://per-central.org/per_reviews/media/volume1/ISLE-2007.pdf

Gott, R., Duggan, S. & Johnson, P. (1999). What do practicing applied scientists do and what are the implications for science education? *Research in Science & Technological Education*, 17, 97–107.

Improving Undergraduate Instruction in Science, Technology, Engineering, and Mathematics: Report of a Workshop, (2003). The National Academies Press, N.W., Washington. Available at http://darwin.nap.edu/books/0309089298/html

Karelina, A. & Etkina, E. (2007). Acting like a physicist: Student approach study to experimental design. *Physical Review, Special Topics, Physics Education Research*, 3, 020106.

Lawson, A. E. (1978). The development and validation of a classroom test of formal reasoning. *Journal of Research in Science Teaching*, 15(1), 11–24.

Lottero-Perdue, E., & Brickhouse, N. W. (2002). Learning on the job: The acquisition of scientific competence. *Science Education*, 86, 756–782.

Next Generation Science Standards, (2013). Available at http://www.nextgenscience.org/next-generation-science-standards Rosengrant, D., Van Heuvelen, A. & Etkina, E. (2009). Do students use and understand free body diagrams? *Physical Review, Special Topics, Physics Education Research*, 5, 010108.

Rosengrant, D., Van Heuvelen, A., & Etkina, E. (2009). Do students use and understand free body diagrams? Physical Review, Special Topics, Physics Education Research, 5, 010108.

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