The Impact of Context on Learning and Epistemology in Physics

By

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Abstract

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This dissertation investigates the impact that various contexts have on student learning and epistemology. This is accomplished by analyzing diverse student populations learning various subjects in physics in distinctive classroom environments at City College New York (CCNY).

Studies in Physics Education Research (PER) have found that many students lack proper conceptual understanding after instruction in physics and that their epistemology, or approaches to learning and doing science, is different from those of experts. The PER community has used these results to develop models of learning and tools for teaching introductory and modern physics with goals that include improving the conceptual understanding, problem solving abilities, and epistemologies.

These curricula are applied in a wide variety of contexts here at CCNY. The student contexts in this dissertation range from high school to graduate school, and the topics range from introductory to modern physics.

We apply many tools commonly used in PER, such as multiple-choice surveys, essay questions, and guided interviews to study these classrooms. We find that PER-based curriculum implemented in these different contexts is able to improve both conceptual understanding and epistemology.

Acknowledgements

I would like to thank Richard Steinberg for his patience and understanding in guiding me throughout my PhD here at City College. Thank you, to my parents for their unwavering support of my goals throughout my life. Many thanks go to my brother for his invaluable feedback and helping me keep my sanity during the rough times.

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CHAPTER 1- Introduction

"…that a monk, whan he is recchelees,
Is likned til a fish that is waterlees,"

"… a monk, when he is cloisterless;
Is like unto a fish that is waterless."

Geoffrey Chaucer
The Canterbury Tales, 14th Century

Learning is the process through which children develop the capability to function successfully in society and adults acquire and develop new skills and knowledge. It is a complex interaction between the new knowledge and the learner's previous knowledge (Vigotsky 1978) that even alters the structure of the brain (Rosenzweig 1972 & 1978, Ferchmin 1978, Greenborough 1979). Context, which comprises the factors of the environment in which learning takes place, also plays an important role in learning (Brown 1989, Rogoff 1984).

By building on the existing body of work about how people learn, Physics Education Research (PER) has developed many tools to improve our understanding of student learning and to teach physics more effectively (McDermott & Redish 1999). Since context plays a role, it is important to understand to what degree it influences student learning and research-based physics curriculum.

The physics-learning environment at City College of New York (CCNY) is contextually rich and varied. It has a culturally diverse student body that comes from many countries and speaks many languages. Its classes range in subject matter from introductory algebra-based physics to modern physics and their curricula range from lecture-based to interactive and research-based.

What impact do different classroom contexts have on student learning and epistemology? How do high school students who are used to succeeding in passive learning classes react to a classroom where they are required to develop and explain their reasoning out loud? How does curriculum requiring significant student interaction fare with a multilingual and diverse student body? How do intelligent and successful students with identical backgrounds but different undergraduate experiences respond to the counter-intuitive implications of non-classical physics?

1.1 - Thesis Structure

In this first Chapter is an overview of the field of Physics Education Research. Next, there is a review of research in areas that are relevant to the work such as: student understanding in introductory and modern physics, astronomy, student epistemology, and context.

Chapter 2 will discuss the results of a three-year investigation of a summer course in astronomy for high school students. The course was specifically designed to effect change in the students' attitudes about the nature of doing science. We analyzed epistemology surveys, instructor evaluations, and short answer questions to understand how the students fared in an unfamiliar learning context.

Chapter 3 will look at the use of PER-based material in the culturally diverse introductory physics lectures and in laboratories at CCNY. In order to measure the effects of PER-based material, we used a conceptual diagnostic in mechanics and videotapes of students in classrooms and laboratories. We will look at an analysis of the data to see how these different contexts affect students.

Chapter 4 will cover a case study of twin brothers working in modern physics, which includes contexts with no classical analogue. The brothers had divergent experiences at CCNY and the study focuses primarily on them working on the twin paradox together. The results are supported by a rubric analysis of the transcript and other interviews of the brothers working on various classical and modern physics problems.

Finally, the last chapter will discuss the relationships between the different investigations and their common threads.

1.2 - Overview of Physics Education Research

Physics Education Research (PER) is concerned with understanding student learning and improving the teaching and learning of physics at all levels of the education system. The modern PER community approaches these goals from a wide variety of perspectives, but one aspect is common: PER uses observations and scientific reasoning to investigate the problem and develops models of learning to create new tools for the improvement of teaching (Reif 1986, McDermott 1990, Redish 1994).

Many physics instructors have seen their students approach a problem by looking at the question and then trying to find the equation whose variables fit the quantities given by the problem. This is an approach that physics instructors strive to dissuade their students from using. To this end, the PER community has developed a methodical and scientific approach to understanding student learning and improving instruction.

Reif suggested a scientific approach to PER in "Scientific Approaches to science education" (Reif 1986). He argued for a systematic method to improve teaching. He

pointed to evidence that students' initial states at the start of a class strongly affects their learning and discusses the advantages of hierarchically organized knowledge that is common to experts and how it is different from novices.

In his 1994 paper, Redish gives an overview of research in cognitive science into the nature of learning (Redish 1994). He outlines four principles derived from this overview to be used to guide investigations.

The first principle states that: "People tend to organize their experience and observations into patterns or mental models". The second principle says that "it is easy to learn something that matches or extends an existing mental model", implying that it is more difficult to learn something that is not similar to an existing mental model.

The third principle states: "It is very difficult to change an established mental model substantially". This means that students can be very resistant to learning a new conceptual framework, which attempts to replace an existing framework, such as replacing non-Newtonian mechanics with Newtonian mechanics.

The final principle states: "Since each individual constructs his or her own mental ecology, different students have different mental models for physical phenomena and different mental models for learning." In other words, the class is composed of individuals with different learning strengths and weaknesses that make generalization difficult. These four principles taken together are meant to provide a framework for researchers to use when conducting Physics Education Research.

Physics education researchers have access to a wide body of preexisting work in education research that spans many disciplines. The National Research Council's

Committee on Developments in Science Learning produced an in-depth overview of education research. The book is called *How People Learn: Brain, Mind, Experience, and School* (1999) and is a primary source for the overarching theoretical framework for this thesis.

How People Learn (or HPL) discusses many important aspects of the study of learning. It makes the distinction between what is traditionally thought of as learning, which is the accumulation of knowledge, and the idea that learning is also about teaching students how to apply their knowledge constructively. HPL also highlights the multi-disciplinary approach used in education research, citing contributions from neuroscience, cognitive psychology, social psychology, and anthropology.

HPL devotes an entire chapter to the comparison of experts and novices. The book discusses many studies of experts and how they differ from novices in their approach to problems in their field. These differences include:

- Experts notice features and meaningful patterns of information that are not noticed by novices.
- Experts have acquired a great deal of content knowledge that is organized in ways that reflect a deep understanding of their subject matter.
- Experts' knowledge cannot be reduced to sets of isolated facts or propositions but, instead, reflects contexts of applicability: that is, the knowledge is "conditionalized" on a set of circumstances.
- Experts have varying levels of flexibility in their approach to new situations.

Meaningful progress for a student in physics can be traced by measuring how their approach to problem solving is similar to that of an expert. Much of the student

evaluation in this thesis is not a measure of student content knowledge but a comparison of student approaches, strategies and ways of thinking with those of experts.

"Transfer" is the ability to apply knowledge in a variety of contexts, especially contexts that differ from the one in which the knowledge is learned. The ability to apply concepts learned in the classroom to situations outside that context is undoubtedly a desired result of instruction. HPL discusses the studies of transfer over the last 40 years and summarizes the key discoveries as follows:

- Initial learning is necessary for transfer, and a considerable amount is known about the kinds of learning experiences that support transfer.
- Knowledge that is overly contextualized can reduce transfer; abstract representations of knowledge can help promote transfer.
- Transfer is best viewed as an active, dynamic process rather than a passive end product of a particular set of learning experiences.
- All new learning involves transfer based on previous learning, and this has important implications for the design of instruction that helps students learn.

Of particular interest to this thesis is the link between transfer and context. The context in which learning happens can influence future transfer of learning to other situations; for example, transferring learning from a classroom context to everyday life contexts.

1.3 - Iterative Cycle of Physics Education Research

We investigate how students learn and develop new teaching materials based on our findings. Those materials must be rigorously tested and refined through an iterative

cycle: research into student understanding leads to curriculum development, which is then implemented in classrooms (see Figure 1.1). This new curriculum is reviewed and tested for further refinement. All aspects of this cycle are informed by and help refine a Model of Learning such as outlined in the previous section.

The Research phase involves using qualitative and quantitative methods to study various aspects of student learning such as their conceptual understanding, epistemology, and attitudes towards learning. This research does not always directly lead to development of new curriculum; it may lead to development of a model of student learning.

The various research methods include multiple-choice surveys, essay questions, interviews and videotapes of students performing various tasks and offer different perspectives on students.

Multiple-choice diagnostic surveys are a common way to identify and classify student conceptual difficulties. The Force Concept Inventory (Hestenes 1992), or FCI, is a widely used survey that tests whether student concepts about force and motion have been changed from everyday concepts to Newtonian concepts. One study analyzed pre-instruction and post-instruction FCI results applied to over six thousand students from various institutions (Hake 1998). The FCI will be described in more detail when it is applied in Chapter 3.

The success and usefulness of the FCI has led to the development of other concept inventories such as the Electromagnetic Concept Inventory (Notaros 2002), the Wave Concept Inventory (Roedel 1998) and the Astronomy Diagnostic Test (Zeilik 2003).

These surveys have been tested and applied to various student populations to catalogue and understand their difficulties with scientific concepts.

Multiple-choice surveys are not only used to catalog student understanding of concepts. They can be used to probe student attitudes about the nature of doing science. Many such surveys have been developed such as CLASS (Adams 2006), EBAPS (Elby 1997), VASS (Halloun 1997), VNOS (Lederman 2002) and MPEX (1998). The implementation and evaluation of these surveys has shown that instruction typically does not change student epistemology significantly. In particular, the MPEX survey will be discussed in more detail in Chapter 2.

Essay or open-ended questions can provide a different perspective on student thoughts. Students are permitted to formulate and express their ideas in their own words.

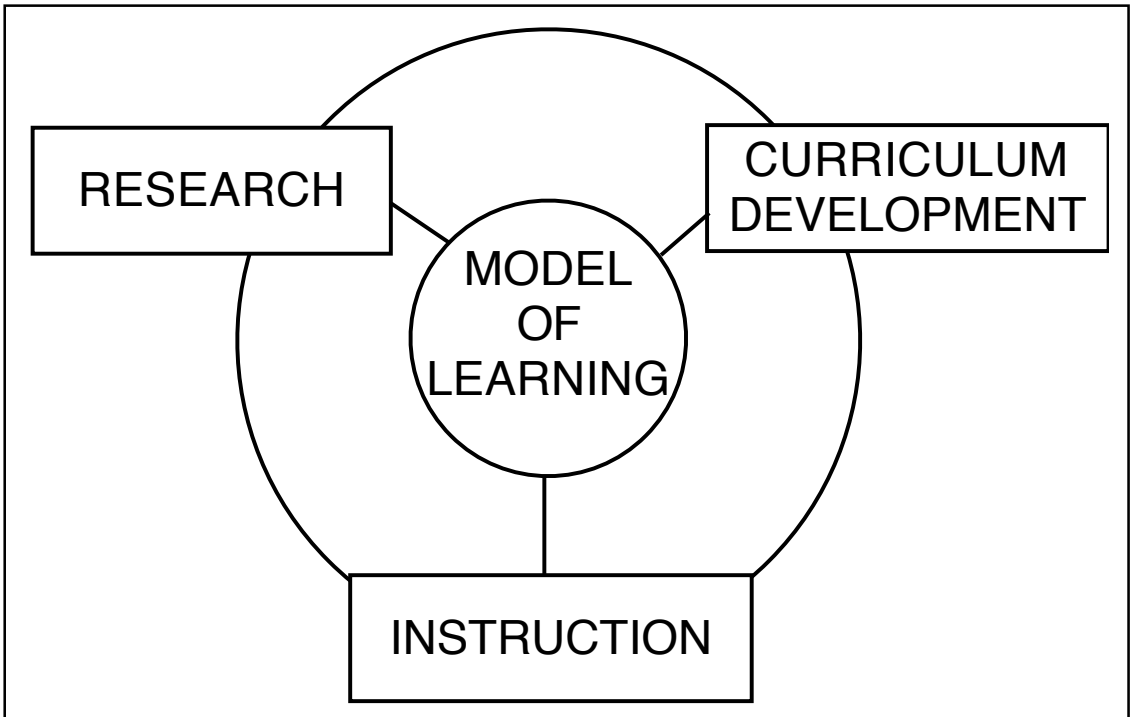


Figure 1.1 - Iterative Cycle for Physics Education Research: The iterative cycle of physics education research.

This is a widely used technique in PER literature (Champagne 1980, Redish, 1997, Steinberg 1997, Scherr 2002). In particular, Champagne did an analysis of student short-answer tests to show that many students continued to have non-Newtonian ideas about force and motion, even after instruction. Analysis of this type of data can be done by a rubric; a rubric is a set of codes used to identify instances of certain behaviors or statements to look for patterns.

Interviews and videotapes of student activities can provide another rich source of data, but they can also prove challenging to analyze. An audio or video record of an interview provides the researcher with many possibilities. A transcript of the interview is produced and it can be used for rubric analysis. Interviews are commonly used in PER (Hammer 1989, Hammer 1994, Trowbridge 1981, Goldberg 1989, Ambrose 1999). Videotaped interviews allow the study of not only the student dialogue, but also their gestures (Scherr 2008) and their physical interactions with each other.

Instruction is the third part of the PER cycle. It provides an opportunity to test new curriculum and to collect data about its impact on the students. From the lessons learned through implementation of the curriculum and the model of learning that it is based on are modified and refined.

An excellent illustration of the entire PER cycle is given in two papers by the Physics Education Research group at the University of Washington (McDermott 1992, Schaffer 1992) regarding student understanding of electric circuits.

The first paper discusses their investigation of student understanding through the use of in-class demonstrations and interviews. They analyze transcripts of the interviews

and student responses to questions given in class to identify common student difficulties. They identified particular difficulties in the following categories:

- Difficulties with concepts related to current.
- Difficulties with concepts related to potential difference.
- Difficulties with concepts related to resistance.
- Inability to relate formal representations and numerical measurements to electrical circuits.
- Inability to reason qualitatively about the behavior of electric circuits.

The second paper uses this information to develop new lab-based curriculum. They describe the instruction strategy as follows:

> "The students perform experiments and draw inferences from their observations to construct the basic concepts of current and resistance. They use both inductive and deductive reasoning to synthesize these concepts into a qualitative model for electric current. This mental picture and set of rules provides the students with a conceptual framework that enables them to predict and explain the behavior of simple circuits. As the students apply the model to circuits of increasing complexity, the need for other concepts, such as potential difference, becomes apparent."

The new PER-based tutorials were put into practice and tested by giving post-instruction questions to over 500 students. Some of the students had used the PER-based material and some had not. Fewer than 50% of the students who did not use the PER-based materials answered the questions correctly whereas over 75% of the student who

took the PER-based material answered correctly. They showed a measureable difference between students who took PER-based material and those who did not.

It is important to emphasize that all aspects of the PER cycle are inextricably linked. Improved instruction is a goal of the research, but it is also a great source of the research data as well as the testing ground for the new material. The model of learning informs curriculum development, but it is a two-way interaction; the model of learning is itself modified and improved by the lessons learned through the process of curriculum development. Similar links can be described for any of the two elements of Figure 1.1.

1.4 - Review of Related Research

1.4.1 - Introductory Physics: Student Understanding

Part of developing a framework for understanding student thought is properly identifying student difficulties. The results of many investigations were used to develop successfully curricula to improve student understanding of the related concepts.

A common example of a student difficulty that has been shown to be very resistant to instruction is the belief that an object's velocity is proportional to the force being applied to it. Students will continue to maintain this belief even after specific instruction on Newton's second law (McDermott 1987).

Investigations of student understanding of kinematics (Trowbridge 1980 & 1981, Peters 1981, McDermott 1987, Aguirre 1988) and dynamics (Viennot 1979, Champagne 1980, Maloney 1984, Halloun 1985, McDermott 1994) identify the specific difficulties that students have with concepts in kinematics. Other studies build on these results to design, test and implement new curriculum (Hewson 1985, Rosenquist 1985, Thornton 1990, Halloun 1987).

While kinematics is the most widely studied introductory subject matter, similar studies have been conducted in other fields. There are studies identifying and analyzing student difficulties with various topics in electricity and magnetism such as electric circuits (McDermott 1992, Schaffer 1992, Fredette 1980, Cohen 1983) electrostatics (Maloney 1985, Guraswamy 1997), and electric and magnetic fields (Fergusson-Hessler 1987, Törnkvist 1993).

Studies of student difficulties in optics range from the nature of light and color (La Rosa 1984, Watts 1985, Saxena 1991) to geometric optics (Goldberg 1986, Galili 1993). Optics instructional strategies have also been developed for classroom instruction (Goldberg 1991, Wosilait 1998) and for teaching through computer simulations (Eylon 1996).

There has also been work done on student difficulties with thermal physics (Warren 1972, Rozier 1991, Kesidou 1993), sound (Linder 1989, Linder 1993), and waves (Whittman 1999). Whittman *et al* used various types of questions to show that students use multiple models to explain the properties of waves.

All of the findings of theses studies are consistent with the theoretical framework described above. They also points to the importance of a conceptual foundation for success in learning physics.

1.4.2 - Astronomy: Student Understanding

An early example of an investigation of student understanding of astronomy concepts is the video *A Private Universe* (Schneps 1989) in which Harvard University students on graduation day were asked to explain the cause of the seasons. Of the 23

students interviewed, 21 were unable to give a scientifically sound explanation of the causes of the seasons or the phases of the moon.

There have been studies that have used quantitative and qualitative methods to investigate student difficulties with specific astronomy concepts such as the cause of phases of the moon (Callison 1993, Fanetti 2001). Fanetti's investigation found many misconceptions shared by students about the causes of the phases of the moon as well as incorrect ideas about the relative scale of the Earth and Moon. Students would describe the phases as being caused by the Earth's shadow even though this is impossible for certain phases such as a gibbous moon.

Other subject matter that has been investigated includes the shape of the Earth (Nussbaum 1976, Jones 1987) and Diurnal motion (Vosniadou 1994, Atwood 1995). The Astronomy Diagnostic Test (Huffnagel 2002, Zeilik 2003) is a widely used multiple-choice test developed to find and categorized student difficulties with a wide range of astronomy concepts such as the phases of the moon, the scale of the objects in the universe and the nature of stars.

Investigations of student learning of astronomy have led to the development and implementation of research-based curriculum (Mcdermott 1996, Zeilik 1997, Zeilik 1999, Adams 1998). Zeilik's investigations describe the development of curriculum based on the findings of investigations into student difficulties and the increase in student understanding.

1.4.3 - Special Relativity: Student Understanding

Previous research on student difficulties with special relativity is limited. A study of undergraduate student investigated understanding of reference frames in India (Panse

1994). Two other studies looked at both undergraduate and graduate students' spontaneous ideas about light in a special relativity context (Villani 1987 & 1990). A case study highlighted a student's belief that time is absolute and how it affects his understanding of special relativity (Hewson 1982).

Two PhD dissertations investigated various aspects of student understanding of special relativity (O'Brien-Pride 1997 and Scherr 2001) such as relativistic two-body problems, time dilation and relativity of simultaneity. This work found that even though students were able to correctly describe relativistic concepts, they often applied non-relativistic concepts when trying to solve problems.

Two papers by Rachel Scherr are of particular importance to this thesis (Scherr 2001 & 2002). In her 2001 paper, Scherr asked students to perform tasks to study their ability to properly determine the simultaneity of events in different reference frames. She found that even after instruction, two thirds of undergraduate students and one third of graduate students were unable to do so. She found that students incorrectly believed that relativity of simultaneity of events depended on when the observers received light signals. In other words, students often solve problems as if the time it takes signals to travel is what accounts for changes in simultaneity of events, even though they state explicitly otherwise.

In her second paper on relativity, Scherr built on her findings in the first paper and used the iterative cycle of Physic Education Research to develop tutorials specifically addressing the difficulties student have with relativity of simultaneity. Versions of these tutorials were used in the PER-based modern physics courses discussed in Chapter 4.

Scherr's work was mostly concerned with improving student understanding of the intricacies of the relativity of simultaneity. The present thesis will focus more on analyzing the students' approaches to solving problems in special relativity and looking at how it differs from student approaches to solving introductory physics problems. The thesis will investigate how the counter-intuitive nature of special relativity affects student learning and epistemology.

1.4.4 - Student Epistemology

Epistemology is defined in the New Lexicon Webster's Dictionary as "the branch of philosophy dealing with the study of the nature of knowledge, its origins, foundations and validity". In this thesis, we are interested in epistemology as it applies to learning science. In the context of education research, we refer to a "student's epistemology" as their attitude or belief about what it is to learn and do science.

Two papers by David Hammer (Hammer 1989 & 1994), focusing on case studies of students in introductory physics, represent the beginning of the study of student epistemology in Physics Education Research. In these papers, Hammer attempts to characterize their epistemological beliefs, or their attitudes about what it is to learn and do science. He interviewed six students over the course of a semester. Through analysis of the transcripts of these interviews, he was able to develop and refine a framework to characterize their different epistemological beliefs (see Figure 1.2) into three dimensions. Hammer went on to use this framework to construct a characterization of students who participated in his study.

The dimension "Beliefs about the Structure of Physics" describes the student attitudes about how physics is organized. A novice-like belief would see the whole of

physics as a collection of separate facts and formulas. An expert-like belief would be that physics is a coherent collection of related concepts. "Weak Coherence" characterizes intermediate beliefs where the student believes that a concept may be related to other concepts but it is only the job of experts to understand those relationships.

The next dimension, "Beliefs about the Content of Physics" describes what the student believes the sum of all physics content is comprised of. A student with novice-like beliefs would see physics content as formulas that can be used in certain situations. A student with expert-like beliefs would see physics as concepts to be understood and interpreted. "Apparent concepts" represents student belief that physics knowledge is comprised of symbols and formulas that are only loosely linked with concepts, whereas "Weak Concepts" means the student believes that there are conceptual links to formulas but that they are the responsibility of experts and not of the student.

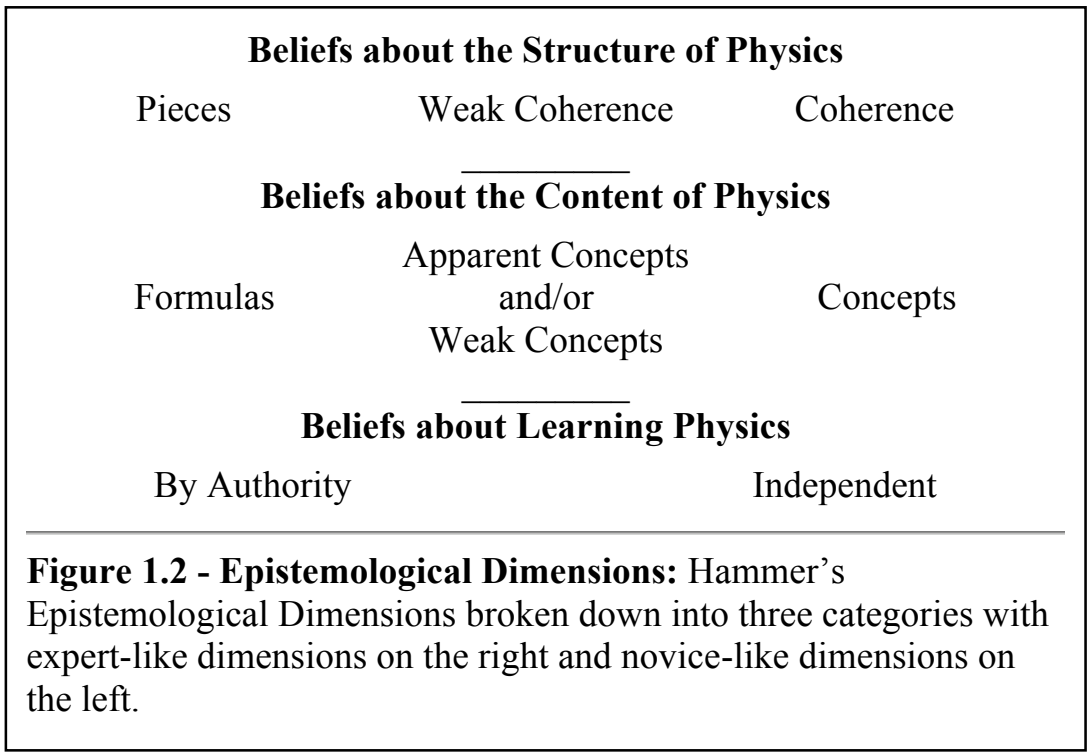


Figure 1.2 - Epistemological Dimensions: Hammer's Epistemological Dimensions broken down into three categories with expert-like dimensions on the right and novice-like dimensions on the left.

The final dimension "Beliefs about Learning Physics" describes the student's belief about what how one should learn physics. An expert-like student would believe they are responsible for developing their understanding of physics. A novice-like student would believe it is sufficient to accept formulas and concepts as given.

The MPEX survey, mentioned in the "Introductory Physics: Student Difficulties" section was developed with these epistemological dimensions in mind (Redish 1998). The items in the survey are each associated with one or more of the epistemological dimensions. The survey will be described in more detail in Chapter 2. There have been other investigations of student epistemology along similar lines (Elby 2001, Hammer 2002, Redish 2004, Louca 2004).

1.4.5 - Context and Student Learning

"Donnie you're out of your element!"

Walter Sobchak,
The Big Lebowski (1998)

In this thesis, context is used to describe features of the learning environment of students. Every class has many aspects that make up its context, including the actual physical environment of the classroom, the curriculum's design and goals, the characteristics of the instructor, and as well as the students themselves. The learning environment for students can vary widely from class to class and college to college. Here is a list of some related contexts that are relevant to this study:

- PER-based class / non-PER class.
- Introductory Physics / Modern Physics.
- High school / Undergraduate / Graduate students.

- Culturally diverse class.

The contrasts between these contexts are what we are interested in observing. We are specifically interested in how student learning is influenced by the context they are in. Brown et al (1998) argue that knowledge is closely tied to the environment in which it is learned and that it is constantly changing and evolving:

> "A concept… will continually evolve with each new occasion of use, because new situations, negotiations, and activities inevitably recast it in a new, more densely textured form. So a concept… is always under construction. This would also appear to be true of apparently well-defined, abstract technical concepts. Even these are not wholly definable and defy categorical description; part of their meaning is always inherited from the context of use."

Brown then goes on to talk about the concepts learned by students as tools: "People who use tools actively rather than just acquire them… build an increasingly rich implicit understanding." This theory of how context affects student learning is common in PER and forms part of the motivation for this thesis: Here at CCNY, we have many courses in uncommon contexts as previously mentioned. How does this affect student learning?

An investigation here at CCNY (Steinberg 2002) found that PER-based curriculum worked well in a multicultural class; they found that students who spoke English as a second language performed comparably to native English speakers.

There is another use of ‘context’ that is relevant: It is often used specifically to describe the setting and/or subject matter of the physics problems posed to the students (for example: Palmer 1997 or Dutch 1997). Throughout this thesis, we will be discussing the different contexts and their influence on the learning environment.

CHAPTER 2 - Astronomy: Exploring Student Approaches to doing Science in an Unfamiliar Learning Environment

"You cannot teach a man anything;
you can only help him discover it himself."

Galileo Galilei

2.1 - Introduction

The majority of high school science classes focus on transmitting content to students; new concepts are presented along with physical motivation and students learn how to apply them to solve typical physics problems. Time, resource constraints and state requirements often lead to testing that does not delve very deeply in student understanding, requiring short answers without explanation of "how" a student found an answer.

Teaching students science should include more that just understanding content; it should include development of an understanding of scientific reasoning. Students would learn to make sense of scientific ideas and how to explain and justify their answers. This chapter covers an investigation of the instructional impact on students' attitudes about the nature of learning and doing science.

As discussed in the Introduction Chapter, researchers have investigated the effect that PER-based classes have on students beyond changes to their conceptual understanding; there has been work investigating student epistemology (Hammer 1989 & 1994) and their attitudes about studying and doing science (Redish 1998).

We investigate the changes to student attitudes about the nature of science due to a course specifically designed to do so. We will not discuss their understanding of

scientific content but rather how they reason and make sense of observations and concepts. This investigation is carried out in an astronomy context but we believe its results are valid in other realms of science.

2.2 - Instructional Context

2.2.1 - Students

The Summer Scholars Program at City College of New York is an enrichment program for grade 9 to 11 high school students from New York City. The program is academically selective. Admission requirements vary from year to year but always include a minimum of a B average and a letter of recommendation from their guidance office. Many of the students come from specialized schools. These are students who are used to being very successful in school.

Student diversity is similar to that of the city, they come from many different ethnic and cultural backgrounds including Asian, African, Middle Eastern, European and Latin American. Several of the students are bilingual and the class is approximately evenly split between male and female.

2.2.2 - Course

The primary goal of the course is not the transmission of content but the development of an understanding of what it is to do and learn science. The content of the course focuses on astronomy, a rich context in which to examine student reasoning and attitudes about doing science. They approach questions such as “How do we know whether the Sun goes around the Earth or the Earth goes around the Sun?” and “How can I account for the apparent motion of the Sun, Moon and stars across the sky?”

We used the PER-based activities from the *Physics by Inquiry* books developed at the University of Washington (McDermott 1996). Over the course of the summer, the students use observations to develop and refine a model to explain astronomical observations.

They start with shadow plots to look at the motion of the sun and how it changes throughout the day and then throughout the year. They perform measurements and thought experiments to model the shape of the Earth. They then include observations of the phases of the moon to expand their model. Next, stars observations are added and the model is refined some more. They actually develop two simultaneous models: the geocentric and heliocentric models of the solar system. Comparing these models, students realize that both can account for sun, moon and star observations very well. By the end of the class, the students are introduced to Newton's laws and discuss whether the laws can be used to choose between the two models.

We present analysis of data collected over 4 summers (see Table 2.1). In "Scientific Approaches to Science Instruction" (Reif 1986), Reif claims that a scientific approach can play an important role in improving instruction. We apply that approach here, using multiple tools to analyze this class.

Year	# of Students
2005	29
2006	30
2007	17
2008	20

Table 2.1 – Class Sizes: Number of students in summer astronomy course by year.

2.3 - Research Methods

Here we describe the methods we used to measure student attitudes about doing science. The three methods are:

- Science Essay Questions
    - Earth-Sun Question
    - Black Hole Question
- Epistemology Survey
- Instructor evaluations.

2.3.1 - Science Questions

To provide a richer source of information on student attitudes, the students were given two science-related essay questions. Essay questions can provide a richer source of data since the students are allowed to expand on their attitudes about science in their own words.

Before and after instruction, they were asked a question about the relative motion of the Sun and the Earth. The question is shown in Figure 2.1. Students were given plenty of time and space to answer the question. They were encouraged to be as thorough as possible. Answers range from one sentence to several pages.

In order to analyze student responses, a rubric was developed to classify the answers. This rubric is a set of rules used to evaluate the student answers and assign each one a number from 1(unfavorable) to 5(favorable).

Ideally the rubric applied by different people will give similar or identical results. Three instructors from the course met to discuss and develop the rubric. This involved

deciding what are favorable and unfavorable answers, providing descriptions for each value between 1 and 5, and creating example answers to guide the person applying the rubric.

Which of the following do you think best approximates the relative motion of the earth and the sun?

A) The earth goes around the sun
B) The sun goes around the earth
C) Neither A nor B are correct
D) I do not know

As best you can, provide a complete scientific argument for your answer.

Figure 2.1 Earth-Sun Question: The question given to students before and after instruction

Favorable responses (number 5) were deemed to be similar to answers that an expert would give. An expert would discuss the evidence in light of both models, highlighting the advantages and disadvantages of each model to explain the observations that were made in the class. The most expert-like answer is "A) The earth goes around the sun", properly supported by an explanation of why the one model is chosen over the other with examples and scientific reasoning. An answer of "D) I do not know" could earn a score of 5 if the student did not think there was enough evidence to pick one model and explained how both models can account for the observations, once again properly supported by examples and scientific reasoning.

Unfavorable responses (number 1) are much simpler to identify. The worst possible scenarios include circular reasoning, irrelevant observations or merely stating the name of the theory to support their answer. Examples of such responses include "The

Earth goes around the Sun because we have night and day" or "The Sun goes around the Earth because of the Copernican theory."

Much time was spent carefully distinguishing between the other codes (numbers 2 to 4). After many discussions and testing on fabricated student responses, the group was able to agree on the rubric shown in Table 2.2.

The second science question posed concerned black holes (see Figure 2.2) and was only administered after instruction. The purpose of this question is to provide a contrast with the Sun-Earth question: Will the students still be able to apply what they learned about scientific reasoning in a different context than the one they were studying?

Which of the following is most accurate?

A) There are things in the universe called black holes from which not even light can escape.
B) While the expression "black hole" is popular in science fiction, it is not something that really exists
C) Neither A nor B are correct
D) I do not know

As best you can, provide a complete scientific argument for your answer.

Figure 2.2 - Black Hole Question: The Black Hole Question as it was presented to students at the end of instruction.

The rubric for the black hole question was developed the same way as the protocols for the Earth-Sun question: A group of instructors from the class discussed each of the grades and came to a consensus on the rubric and the included examples. The rubric is shown in Table 2.3. Results will be discussed in the next section of this chapter.

Score	Description	Example Answers
5	Student cites observations/ experiments distinguishing between 2 models and supports choice with proper explanation relevant to their answer (regardless of whether student answers B or D).	**D:** "We can reproduce the relative motion of all celestial bodies by having the earth stationary and having the sun, moon and stars revolve around the earth at different rates (Supported with specific examples). We can also reproduce the same results by having the moon revolve around the earth, the earth revolve around the sun, and the stars be stationary and far away." **B:** "Although we can reproduce our observations in either model, gravity suggests the sun centered model is better because the object with less mass will move much more than the object with greater mass (supported with Newton's laws)."
4	Student cites observations/ experiments distinguishing between models in a consistent way but explanation is not developed or is incomplete.	**D:** "I don't know because both models can account for the apparent motion of the stars in the sky" **B:** " B is a better answer because its easier to explain the results that way." **D:** "Neither A nor B are correct becasue the relative motion depends on one's perspective..."
3	Student refers to relevant observation and experiments but part of explanation is erroneous or problematic OR student recognizes an inability to answer to the question.	**B:** "...because the sun is bigger than the earth so the sun pulls harder." **B:** "...because the planets don't fit on the celestial sphere." **D:** "...I don't know because I have nothing on which to base my answer."
2	Student cites relevant observations/experiment in support of their choice, thoughts are not clearly connected, little or incorrect development of ideas or reasoning, no distinction between models is made.	**B:** "the sun moves around the earth because i see the sun move across the sky." **B:** "The seasons are caused by the fact that the earth moves around the sun." **B:** "...it has something to do with the sun having a larger mass than the earth"
1	Student's use of jargon, authority, circular reasoning, or irrelevant observations/experiments represents a significant part of their answer.	**B:** "The earth goes around the sun because of the Copernican theory." **B:** "The earth goes around the sun because it takes a year to go through the seasons." **B:** "The earth goes around the sun because we have day and night."

Table 2.2: Earth-Sun Question Rubric: Rubric used to score answers to the Earth-Sun question. Scorers were provided with example answers to guide them.

Score	Description	Answer
5	Student cites relevant observations/experiments supporting their choice with correct explanation OR Student selects "I do not know" and supports selection with recognition that scientific development is needed to justify it properly.	**D:** "I have heard of black holes but do not know of the experimental evidence for them, which would be necessary to confirm that they exist" **D:** "I do not know the scientific justification of black holes myself but understand that others have gone through the necessary steps to argue their existence". **A:** "... if we could observe a star that seems to be orbiting an unseen object, then it is a possible black hole..." (supported and described)
4		**D:** "I do not know because it is not something I have seen for myself".
3	Student cites relevant observation and experiments but part of explanation is undeveloped or problematic OR student selects "I do not know" but does not support their answer in any way.	**A:** "Light cannot escape from black holes because their gravity is very strong". **D:** "I do not know the answer".
2		**A:** "Einstein showed that if gravity is strong enough, light cannot escape".
1	Student's use of jargon, authority, circular reasoning, or irrelevant observations/experiments represents a significant part of their answer.	**A:** "Stephen Hawking discovered black holes". **A:** "Black holes are big because light cannot escape". **A:** "They exist but you can't see black holes because no light comes from them".

Table 2.3: Black Hole Question Rubric: The rubric used to assign a score to student answers to the Black Hole question. Scorers were provided with example answers to guide them.

2.3.2 - Epistemology Survey

Several surveys have been developed to probe student epistemology. These include CLASS (Adams 2006), EBAPS (Elby 1997), VASS (Halloun 1997), VNOS (Lederman 2002), and MPEX (Redish 1998). We decided to use one of these surveys to see how the students describe themselves and how well those responses would correlate with other measurements of their epistemology.

A modification of the MPEX, or Maryland Physics Expectations, was given to the students. The survey is a set of statements about the nature of physics that the students are asked to rate from

- 1 = Strongly Disagree

  to

- 5 = strongly agree

The student responses are compared with those an expert would give. In order to have all the questions on the same scale, each response was rescaled to range from:

- 1 = Strongly Unfavorable Response

  to

- 5 = Strongly Favorable Response.

The statements have been rigorously tested and refined over several years and have been tested on multiple populations at 15 universities. The seventeen items, shown in Table 2.4, were taken from the survey to give to the students before and after the instruction.

1	When real life experiences differ from what is learned in a science textbook the real life experience should be ignored in order to learn the science.
2	It is very hard to understand scientific ideas in an intuitive sense; they should just be taken as given.
3	Knowledge in science consists of pieces of information, each of which applies primarily to a specific situation.
4	To know science is to be able to recall equations, laws, definitions and theories.
5	Creativity is a useful skill that is often utilized in learning science.
6	Learning science is a matter of acquiring knowledge that is specifically located in the definitions, principles, and equations given in class and/or the textbook.
7	In learning science, it is not necessary to make connections between science concepts and real life experiences.
8	A significant problem in science courses is being able to memorize all the information that I need.
9	In solving problems in science, if a calculation provides a result that is significantly different than what was expected, the calculation should be trusted.
10	Science laws have little to do with everyday life.
11	Being able to recall formulas and definitions about a topic in science shows an understanding of that topic.
12	Often, a scientific principle or theory just doesn't make sense. In those cases you have to accept it and move on because not everything in science is supposed to make sense.
13	Each field of science has its own set of theories, equations, and definitions, few of which have connections with other fields
14	What is observed in real life doesn't always match scientific theories because those theories only apply to laboratory situations.
15	A good textbook is the most useful tool in learning science.
16	When learning science, understanding the concepts and the connections between them is more important than memorizing formulas and definitions.
17	The most crucial thing in answering a question or solving a problem in a science class is to find the right definition or equation to use.

Table 2.4 Epistemology Survey: List of questions taken from the MPEX and given to students before and after instruction.

Each of the survey questions can be associated with one or more of the epistemological dimensions developed by Hammer (see section 1.4.4). The associations are shown in Table 2.5 (Redish 1998). As an example, Question 3 probes whether students believe that knowledge in science is made up of individual pieces of information or is a large coherent framework. Experts disagree with this statement as they see the large-scale framework of scientific knowledge, whereas beginners will see each concept or formula as something that is applied in specific situations.

Question 16 is an example of a question that probes two of the epistemological dimensions: concepts and coherence. This is a statement that experts will agree with.

Dimension	Questions	Description
Reality Link	1,7,10,14	How does science learned in the classroom relate to what goes on in real life.
Independence	2,5,6,11,12,16	How one must process data that is received in a science class.
Coherence	3,8,9,13,16	How the other science disciplines connect with one another.
Concept	5,6,11	How one learns science.

Table 2.5 Dimensions of Survey Questions: Relationship between each of the survey questions and one of Hammer's Epistemological Dimensions.

2.3.3 - Instructor Evaluations

After instruction, the instructors and teaching assistants involved with the course were asked to fill out a survey to evaluate their students' epistemology. They were asked to evaluate them separately for each of Hammer's epistemological dimensions (see section 1.4.4). The survey is shown in Figure 2.3.

As part of a study on epistemological beliefs in the summer-scholars class please fill out the following survey:

The following is a survey to gauge your opinion of where the students in your summer scholars' class are when it comes to 5 dimensions of epistemology. The following text gives a description of each of the 5 dimensions and the two extreme cases (Favorable, Unfavorable)

Reality link
Concept
Coherence
Independence

Here is a list of descriptions of answers from Favorable to Unfavorable:

	Reality Link	Concept	Coherence	Independence
Favorable	Believes ideas earned in science are relevant and useful in a wide variety of real contexts	Stresses understanding of the underlying ideas and concepts.	Believes science needs to be considered as a connected, consistent framework.	Takes responsibility for constructing own understanding.
Unfavorable	Believes ideas learned in science have little relation to experiences outside the classroom.	Focuses on memorizing and using formulas.	Believes science can be treated as unrelated facts or "pieces".	Takes what is given by authorities (teachers, text) without evaluation.

Figure 2.3 Instructor Evaluation Survey: This is the survey given to teachers to evaluate each of their students at the end of the semester.

2.4 - Results

All results are taken only from the data that can be matched for all the tools we used: the two science questions, the epistemology survey, and the instructor evaluation. Data was collected for 96 students total. Data from students who missed either of the science questions or the epistemological survey were removed from the set. This gave a total of N=80 for matched data. All of the results are summarized in Appendix A.1.

2.4.1 - Science Question Results

For the Earth-Sun Question, prior to instruction, 93% of the students chose "A) The Earth goes around the Sun". Several sample answers are given in Table 2.6a and Table 2.6b below. Each student is assigned a pseudonym that reflects their ethnicity and gender to hide their identities. They often used authority and/or circular reasoning to justify their answers, such as the answers given by Nikul and Amir. Other students, such as Ye, refer to the role gravity plays in determining what orbits around what, but they make errors and leave omissions in their description.

After instruction, the student answers have changed dramatically: 45% of the students answered "D) I do not know" and 50% chose "A) The Earth goes around the Sun". The fact that there is no consensus on the final answer is representative of the instructional philosophy of the course. Using observation and reasoning, students developed their scientific model of the solar system throughout the semester. Instructors gave them support and guidance but never gave authoritarian answers. Only about half the students felt there was sufficient evidence by the end of the semester to choose one model over the other.

Name	Pre-Instruction Answer	Post-Instruction Answer
Nikul	**SCORE = 1: A** "We know that sun is stationary and does not move. But, earth moves and is not stationary. Also by looking at the Heliocentric Theory, we know that earth revolves around the sun and that's how we get our years."	**SCORE = 4: A** "Before Newton's Laws were introduced, both A and B would have been possible. If A were the case, then the sun would move clockwise around the earth, and if B were the case then the earth would move counter-clockwise around the sun. Both would account for the same conditions. However Newton explained that the more mass an object has the more gravitational pull. From our observations the earth has less mass than the sun, so the gravitational pull is greater. Also we discussed Mars coming closer and the only way that could be accounted for is if the earth and Mars orbits around the sun, and as they orbit the distance between them changes. The laws of motion and force support that the earth goes around the sun."
Hadith	**SCORE = 1:A** "The earth goes around the sun because the different hemispheres of the earth receive the sun at different angles at different times of the day. The sun- is always in the same position when it is visible. Therefore, the sun does not change position, rather, the earth does."	**SCORE = 5: D "**The relative motion of the earth and the sun can be accounted for in both ways. Through ray observation. I saw both ways to be accurate. I saw that the earth can go around the sun counter clockwise and account for the relative motion of the sun and the earth. I also saw that the sun can go around the earth clockwise and it still would account for the relative motion of the sun and earth. There is no reason to choose another model using only the sun and earth's relative motion. Therefore, I do not know which model is better because with this information, the results are reproduced with the same amount of accuracy."

Table 2.6a - Example Answers to Earth-Sun Question: Characteristic verbatim pre and post answers to the Earth-Sun question, given with their score.

Name	Pre-Instruction Answer	Post-Instruction Answer
Ye	**SCORE = 2: A** "This can be explained scientifically. The sun is a much larger planetary body therefore exerting a stronger gravitational pull on earth than the earth does on the sun therefore it's impossible for the sun to rotate around the earth.."	**SCORE = 5: D** "From our (human) point of view, the path the sun takes across the sky can be explained by either A or B. I know this because I observed with my own eyes both a helio and geo centric model. Repeated experiments show the same path of the sun for either model. Not only that, but the path of the moon and phases can also be accounted for by either model. In the helio model, the moon may be either revolving around the earth clockwise or the earth can be revolving around the moon counterclockwise to account for the apparent path/phases of the moon..… …Not only can either model explain the daily motions of the sun and moon, but both can also explain the annual motions of the sun and stars. GEO:-sun revolves around the earth in and up-and-down orbit, or with the earth on a tilt (in respect to the sun's orbit) - stars revolve around the earth on a "sphere" far from earth. HELIO:-earth revolves around the sun in an up and down orbit, or on a tilt (in respect to it's orbit-stars are fixed very far from the earth, explaining the annual observations we see of the stars) Since both models account for all our observations well, we cannot prove or disprove either model to be correct or incorrect."
Amir	**SCORE = 1:A** "It takes 365.25 days for the earth to go around the sun making a full year."	**SCORE = 4: A** "I feel that the earth goes around the sun because of the sun's gravitational pull that it exhibits on the earth and the other planets. Most things can be explained in both the heliocentric model and the geocentric model. However some things does not go around the earth like the planets. Sometimes Mars can be relatively close under a telescope and other times it is extremely far. The planets also do not follow the same pattern as the stars as seen from the earth. If you put these observations on the heliocentric model, it works. We also discovered that the moons of Jupiter revolved around Jupiter in a circular motion. We observed that the small things tends to revolve around bigger things because Jupiter looked 200 times bigger than the moons that was around it. From that observation and others, like our moon revolving around the earth, I conclude that the earth goes around the sun."

Table 2.6b - Example Answers to Earth-Sun Question: Characteristic verbatim pre and post-instruction answers to Earth-Sun question.

Many of the students who choose D, such as Hadith, describe how both models can be used to account for the daily motion of the Sun, Moon and stars. Students who scored high and chose B provided justifications for choosing the Earth around the Sun instead of the other way around. Nikul described how the introduction of Newton's Laws and gravity supported the earth going around the sun. Other students, such as Amir, described how the geocentric model became much more complicated and unwieldy when the planets were incorporated into the model.

For the Black Hole question, which was only given after instruction, 95% of the students chose "D) I do no know". Some typical answers are shown in Table 2.7 below. Many students acknowledged that they did not know but did not offer much in terms of a description of what would be considered sufficient evidence to justify the existence of black holes. A weakness of the student answers is that few students said that black holes exist and that they knew what scientists needed to do to find them.

The rubrics were applied to the student answers to both science questions from 2005 to 2008. Two separate graders applied it independently and then compared their answers to discuss any differences and reached a consensus on the final code. The graders' initial coding were initially very close to each other, more that 80% of their codes agreed and none differed by more than 1 point. When there was a difference, the graders met and reviewed the answer together to come to a consensus about what the final score should be.

Name	Answer
Valini	**SCORE = 3: D** "I do not know the answer to this question simply because I have not covered this topic during my studies of astronomy. I do not have an adequate amount of knowledge concerning black holes. So I therefore cannot make any such assumptions concerning this topic. My knowledge ranges from the stars to the sun to the moon and just about everything concerning the celestial sphere but I have yet to understand the concepts behind Black hole and the universe."
Phil	**SCORE = 5: D** "The is answer is that I do not know. The reason for this is because I am unfamiliar with the topic of black holes, and since neither A nor B give me proper reasoning in their statements, I do not know if they are accurate. A makes a statement that light cannot escape black holes. However, since the statement does contain any support or observations to prove this statement correct, there is no way for me to tell how accurate the statement is. Similarly, B does not give any support for its statements that black holes do not exist so I cannot tell how accurate B is either. If b stated a reason why black holes cannot exist, then you could know that the statement is accurate. However since neither of the statements give support for their statements, it is impossible for me to know how accurate the statements are in their claims. Another reason why I cannot tell how accurate the statements are is because neither of them answer a simple "how do you know" question because they give no support."
Leigh	**SCORE = 4: D** "I do not know because I have never observed a black hole. Although scientists believe that black holes exist, there is no concrete evidence. It does make sense that something as dense as a black hole can attract planets and stars to it to form a galaxy, but I only know this because I read it in a book. There could be other possibilities and ways in which galaxies can form. A black hole can lead you to a different dimension, a different world, for all we know. In this course I learned not to believe anything until I see that it happened or I understand how it happened."
Jan	**SCORE = 5: D** "I think that D is most accurate for I have no observations which prove that black holes exist or don't exist. Unless I've seen it or someone else [with a very truthful character] has seen it, [and survived] I will not accept the existence or non-existence of black holes. I will accept the existence or non-existence of black holes if enough evidence is provided to me through experiments I can utilize and gain data that supports an argument."

Table 2.7 - Example Answers to Black Hole Question: Sample verbatim answers to the Black Hole question, including the score.

In order to compare pre-test scores with post-test score we use the Normalized Gain (G_N), defined as:

$$G_N = \frac{(\text{PostScore\%} - \text{PreScore\%})}{(100\% - \text{PreScore\%})}$$

The regular Gain is the difference between the post-score and the pre-score. The G_N is found by dividing this score by the maximum possible Gain in order to normalize it. G_N gives a measurement of the fraction of the maximum possible increase in their score. When measure this way, the gain will be 1.00 whenever the student achieves the maximum possible gain from their initial score. For example, if one student's score goes from 20% to 60% and another student's score goes from 60% to 80% they will both score the same normalized gain of 0.50 since they both increased their score by 50% of maximum possible gain based on their initial score. The results are shown in Table 2.8 below.

	Earth - Sun			**Black Hole**
	G_N	**Pre**	**Post**	**Post**
2005	0.52	1.45	3.30	4.10
2006	0.71	1.36	3.96	3.52
2007	0.74	1.47	4.07	4.00
2008	0.80	1.30	4.25	3.90
Average	**0.69**	**1.39**	**3.89**	**3.85**

Table 2.8 - Science Questions Summary: Summary of results for Earth-Sun and Black Hole questions broken down by year.

The Earth-Sun question gains for each year are high. As described earlier, a favorable response to the Earth-Sun question is not solely tied to the student's ability to reproduce the details of various experiments and facts learned throughout the course. In

order to score high on the rubric the student must be able to present those ideas in the context of how it relates to choosing one model over the other. The student must be able to discuss and properly interpret the results of their observations or explain how Newton's laws can be used to choose one model over the other.

In their post-instruction answers the students demonstrated a clarity and confidence of their understanding of the concepts that was far more advanced than when they first started the course.

2.4.2 - Epistemology Survey Results

The pre- and post-instruction answers to the 17-question survey were entered and rescaled so that all favorable answers are 5 and unfavorable answers are 1. The scores along each dimension and the overall averages are shown in Table 2.9 and the normalized gains are shown in Table 2.10.

The students scored relatively high on the Epistemology Survey before instruction, an average of 3.77 out of a possible 5.00. This is very different from the pre-instruction Earth-Sun science question of 1.39. It is possible that many students, when presented with a list of statements about the nature of science, can identify which statements would be considered favorable by experts but that they do no put them into practice themselves. The survey merely asks them what they should do when thinking about science, the essay questions asks them to put these ideas into practice. Their average post-instruction result was 3.94 giving $G_N = 0.14$. The students showed modest gains.

	Reality		Ind.		Coherence		Concepts		Average	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
2005	4.35	4.24	3.89	4.00	3.64	3.69	3.74	3.90	3.84	3.90
2006	4.18	4.23	3.85	4.15	3.69	3.76	3.79	4.02	3.78	3.94
2007	4.22	4.30	4.00	4.24	3.74	3.79	3.89	4.11	3.83	4.06
2008	4.20	4.51	3.20	3.42	3.29	3.47	3.07	3.38	3.63	3.88
Total	**4.23**	**4.32**	**3.73**	**3.95**	**3.59**	**3.67**	**3.61**	**3.85**	**3.77**	**3.94**

Table 2.9 - Epistemology Survey Results: Average Score on Epistemology Survey broken down by year and epistemological dimension.

G_N	Reality	Ind.	Coherence	Concepts	Average
2005	-0.17	0.10	0.04	0.13	0.05
2006	0.06	0.26	0.05	0.19	0.13
2007	0.11	0.24	0.04	0.20	0.19
2008	0.39	0.12	0.11	0.16	0.19
Total	0.11	0.17	0.06	0.17	0.14

Table 2.10 - Gains for Epistemology Survey: Summary of Normalized Gains (G_N) from the Epistemology Survey, broken down by year and epistemological dimension

2.4.3 - Instructor Evaluation Results

The results of the instructor evaluations are summarized in Table 2.11 below. The average instructor evaluation of their students was 3.66 +/- 0.80. There are no significant differences between the four dimensions. 21% of the students score below 3.0. These students scored an average 3.59 on the Earth-Sun posttest whereas the students who score above 3.0 scored and average of 3.97.

	Reality	Ind.	Coherence	Concepts	Average
2005	3.35	3.43	3.38	3.43	3.40
2006	3.65	3.60	3.54	3.44	3.56
2007	3.97	3.73	3.93	3.83	3.87
2008	3.85	3.95	3.90	3.90	3.90
Total	3.69	3.67	3.66	3.63	3.66

Table 2.11 - Instructor Evaluation Results: Results of the Instructor Evaluations, scaled such that 1 is unfavorable and 5 is favorable.

2.4.4 - Correlations

The sections above measured student epistemology using three methods: science essay questions, an epistemology survey and instructor evaluations. Here we calculate the correlation coefficients between these three measures of epistemology in Table 2.12. The list of variables correlated is:

- Earth-Sun pre-test
- Earth-Sun post-test
- Epistemology survey pre-test
- Epistemology survey post-test
- Instructor evaluation
- Earth-Sun Gain (post-score – pre-score)

Each of the research methods probes student epistemology in a different way. Student thinking about science is often fragmented and dependent on the context (Louca 2004), so it is not surprising that there are low correlations between all of the post-instructions surveys: Earth-Sun Post, Epistemology Post and Instructor Evaluation Post.

The Epistemology Post results have the lowest correlations with all of the other post-instruction measurements.

The highest correlation is between the epistemology survey pre-instruction and the epistemology survey post-instruction. This indicates that even though there were small gains for the survey, the structure of the student responses to the survey did not change significantly after instruction.

The correlations between Instructor Evaluations and both the Earth-Sun post result and the Earth-Sun Gain result are 0.16 and 0.15 respectively. This suggests that the Instructors are evaluating their student improvement in the class rather than their epistemology.

	Earth-Sun pre	**Earth-Sun post**	**Epist. Survey pre**	**Epist. Survey post**	**Instructor Evaluation**	**Earth-Sun Gain**
Earth-Sun pre	**1.00**	0.13	-0.02	-0.08	-0.01	-0.44
Earth-Sun post		**1.00**	-0.08	-0.07	0.16	0.83
Epist. Survey pre			**1.00**	0.61	-0.01	-0.06
Epist. Survey post				**1.00**	0.09	-0.02
Instructor Evaluation					**1.00**	0.15
Earth-Sun Post - Pre						**1.00**

Table 2.12 - Correlations: Correlations between various measures of student epistemology.

2.5 - Supplemental Investigation into Teacher Epistemology

Here we look at the effect of this course on a very different group. In this case the students are pre-service teachers starting a two-year graduate program to train them for work in the New York City school system.

Teachers in the program take both pedagogical and content courses. At the beginning of the program, they take a 2-week intensive course that includes an astronomy unit similar to the one taken by the high school students. Many of the teachers are from all over the country and come to New York specifically for the program. In this section, "teachers" will refer to the pre-service teachers who are the students in the class and "instructors" will refer to those who are teaching the class.

Data collected for the teachers was limited to the Earth-Sun science question and the epistemology survey and it covers two years: 2006 and 2007. As with the high school students, all results are taken only from the data that can be matched for all the tools we used: the two science questions and the epistemology survey. We collected data for 112 students, N=96 students remained after unmatched data was removed.

2.5.1 - Science Question Results

Example pre-instruction and post-instruction answers are shown in Table 2.13 and the overall gains are shown in Table 2.14. The average gains for the teachers ($G_N = 0.55$) are lower than those for the high school students ($G_N = 0.69$). There are two possible explanations for this result. One is that the teachers take an intensive two-week course and the high school version of the course lasts 6 weeks. The shorter time spent on the subject matter may lower the impact on student attitudes. Another possibility is that the teacher attitudes may be less pliable due to age or four years of college experience.

2.5.2 - Epistemology Survey Results

The pre- and post-instruction answers to the 17-question survey were entered and rescaled so that all favorable answers are 5 and unfavorable answers are 1. The scores along each dimension and the overall averages are shown in Table 2.15 and the normalized gains are shown in Table 2.16. The dimensions are the same as defined earlier in Figure 1.2.

Name	Pre Instruction Answer	Post Instruction Answer
Jane	**SCORE = 1:** "It has been found that the Earth and all of the other planets revolve around the sun due to scientists trying to explain the calendar year and seasons that we experience on Earth…"	**SCORE = 4:** "Using our observations of the sun, moon and the earth both the geo and the heliocentric models accounted for our observations. Our observations of planetary motion of other planets (they do not move with the stars and have their own mass and revolutions) **heliocentric model where the earth revolves around the sun best explains our observations. If we did not have observations of the planets however, we would not be able to choose one model over the other since there are ways that both models explained our observations"
Josh	**SCORE = 1:** "The earth orbits around the sun, which takes 365 days to complete, while simultaneously the earth is rotational which takes 24 hrs"	**SCORE = 4:** "A heliocentric model (earth around sun) and a geo model (sun around earth) could both account for what we see happen (our observations) we see that the sun, moon, stars and planets in our vision rise in the east and set in the west. This would suggest that the earth if spinning and rotating around the earth. However, we could easily account for these observations by thinking of the sun going around the earth, the earth staying still, and all things rotating around the earth. Therefore at this time, I have no idea how to prove that the earth goes around the sun."

Table 2.13 - Example Answer to Earth-Sun Science Question for Teachers: Sample pre- and post-answer to the Earth-Sun question, given with their score.

	Earth – Sun Question	
	2006 (N=37)	**2007 (N=59)**
Pre-Instruction	1.32	1.48
Post-Instruction	3.41	3.31
G_N	0.57	0.52

Table 2.14 - Earth-Sun Question Gains for Teachers: Gains (G_N) for Earth-Sun Science Question for the teachers.

G_N	**Reality**		**Indep.**		**Coherence**		**Concepts**		**Average**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
2006	4.42	4.41	3.92	4.22	3.79	3.99	3.59	3.98	3.90	4.13
2007	4.36	4.64	3.94	4.27	3.88	4.01	3.63	4.16	3.91	4.23

Table 2.15 - Epistemology Survey Results for Teachers: Average score on epistemology survey broken down by year and epistemological dimension.

G_N	**Reality**	**Indep.**	**Coherence**	**Concepts**	**Average**
2006	-0.02	0.27	0.16	0.28	0.21
2007	0.45	0.31	0.12	0.39	0.30
Total	0.27	0.30	0.13	0.35	0.26

Table 2.16 - Gain for Epistemology Survey for Teachers: Summary of Normalized Gains (G_N) from the epistemology survey, broken down by year and epistemological dimension.

2.6 - Summary

The high school students came into the course with limited or no ability to reason scientifically about a problem. Their pre-instruction responses to the Earth-Sun scientific reasoning question were predominantly "B: the Earth goes around the Sun" and show widespread circular reasoning and deference to authority. Many students believed that citing Copernicus or Newton constituted scientific reasoning.

By the end of the semester, their responses changed significantly. Their answers were evenly split between "B: The Earth goes around the Sun" and "D: I don't know". Their ability to describe the steps taken to properly justify one model over the other improved greatly. The averages of all the measurements of student epistemology for the high school students are summarized in Figure 2.4.

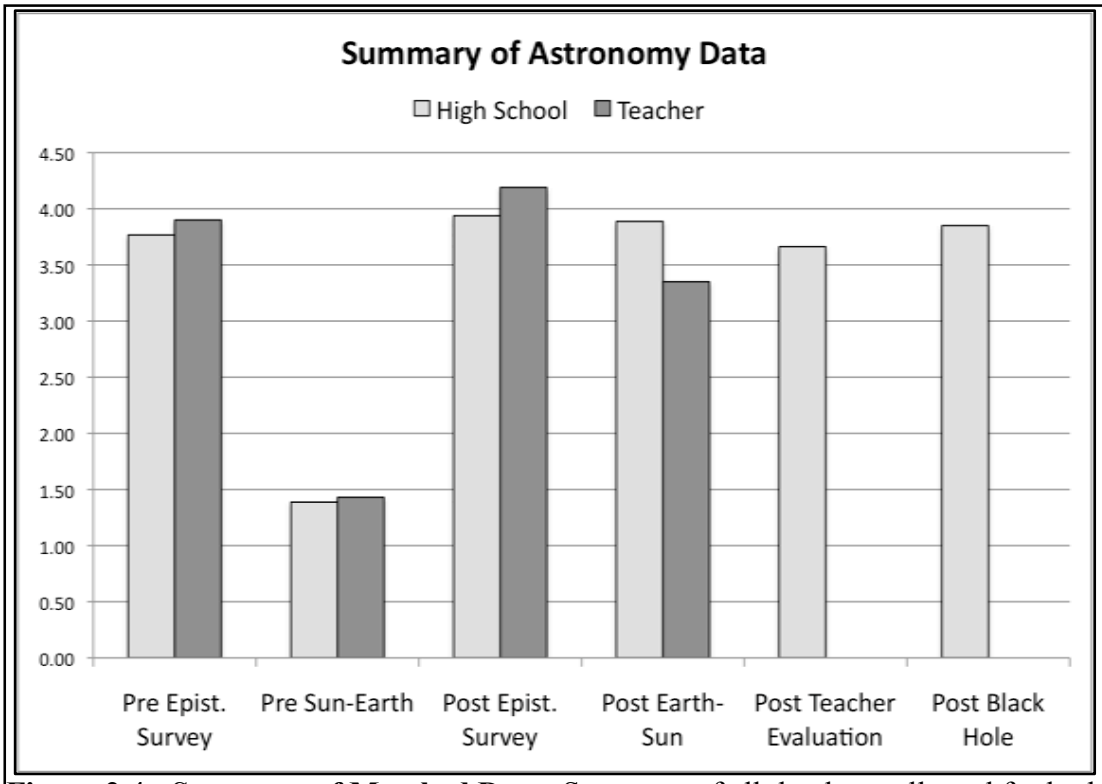


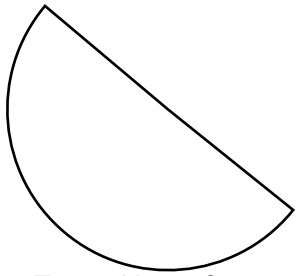
Figure 2.4 - Summary of Matched Data: Summary of all the data collected for both High school students and the teachers for the summer astronomy course.

Both the epistemology survey and the black hole question support these results. In particular, the fact that student answers to the black hole questions were positive indicates a robust change to their approaches to scientific reasoning. Their ability to reason scientifically is not limited to the material covered in the course.

The results of the investigation into the course for teachers are consistent with the high school student results. Most of the teachers recently completed university degrees and displayed pre-instruction epistemologies that were very similar to those of the high-school students. Their undergraduate experiences did not provide an advantage in producing a complete scientific reasoning.

These high school students were all taking a PER-based course for the first time and were not used to being asked to describe and justify their answers. Plunged into this unfamiliar environment, the students quickly adapted to the new curriculum. Analysis showed that this course, designed specifically to positively impact their attitudes about doing science, had a strong impact on their epistemologies. It also showed a strong impact on their understanding of the astronomy content. The student success rate on the question shown in Figure 2.5 was over 95%.

1. A teacher in Seattle made the observation of the moon shown at right.



A) At approximately what time of day did the moon transit the local celestial meridian on the day of this observation? Explain.

B) At approximately what time of day was the observation made? Explain your reasoning.

C) While the teacher in Seattle was recording his observation, a teacher in Boston, made an observation of the moon. Would she have been able to see the moon? Explain.

D) Four days later, the teacher in Seattle observed the moon again. What phase did he see this time? Explain your reasoning.

Figure 2.5 - Sample Exam Question: Example question on the final exam. Correct responses were given by over 95% of the students.

CHAPTER 3 - Introductory Physics: Assessing Student Learning in PER Courses in a Diverse Setting

"Much learning does not teach understanding"

Heraclites, On Nature, 5th Century BC

3.1 - Introduction

When City College of New York was founded in 1847, one of its stated goals was to provide access to higher education for poor and immigrant children from the city. For the last 160 years CCNY has remained a first-rate option. CCNY students and faculty speak 85 languages and come from over 120 countries. With these levels of cultural diversity come new challenges due to different levels of English proficiency and differences in cultural norms.

Students taking introductory physics courses at CCNY are immersed in a variety of unique contexts and they study in some of the most culturally diverse classes in the country. Depending on which Introductory Physics course section they end up in, students will experience one of two very different learning environments: They will either take a PER-based section developed through Physics Education Research or a non-PER section. From 2004 to 2007 they also took PER-based and non-PER labs.

Students are exposed to a variety of different learning environments within City College: including multiple class and lab designs. The question asked in this chapter is: How will these contexts impact their learning experience? It is of particular interest that the PER-based curriculum was originally designed and tested in environments which are less diverse than CCNY, such as the University of Washington.

An investigation of PER-based classes (Steinberg 2002) has already been performed at CCNY. Steinberg found that both native English speakers and ESL (English as a Second Language) students show marked improvement under PER-based reform at City College. This work will expand on that paper with a study of multiple classes over eight years.

First we will describe these various instructional contexts, traditional and PER-based classrooms, in more detail. Next, we will describe the collection and analysis of the Force Concept Inventory survey, designed to measure student understanding of Newtonian dynamics. Finally, we will look at the analysis of videotapes of students working on the introductory labs.

3.1.1 - PER-based Lectures

Since 1999, CCNY has offered PER-based sections of the calculus-based introductory physics courses PHYS 207 and PHYS 208.

For the introductory physics sections studied, there were three hours of lectures per week, as well as recitations every week, and seven labs spread out over the entire semester. The difference with the PER-based classes lies in how they use the class time. It is not a typical class setting where the professor stands at the front of the class and presents the course material to the students in lecture format, occasionally presenting demonstrations and working out problems on the board.

In PER-based classes, for some of the class time, the students are seated at tables in groups of 4 or 5. These groups are usually self-selected but it is sometimes necessary for the professor to change groups around to improve participation. During the group work times student typically use “Tutorials in Introductory Physics” (Mcdermott 1996).

These tutorials are explicitly based on the results of Physics Education Research. The students are encouraged to discuss their ideas out loud and come to an agreement as a group with minimal interference from the instructors.

There are typically one or two 'facilitators' who go from table to table observing the students. The facilitators do not answer direct questions about how to resolve the problem at hand; they try to ask questions to help students further their discussion. This is often difficult for first-time facilitators, who are used to answering questions more directly and very much want to help the students get to their answers more quickly.

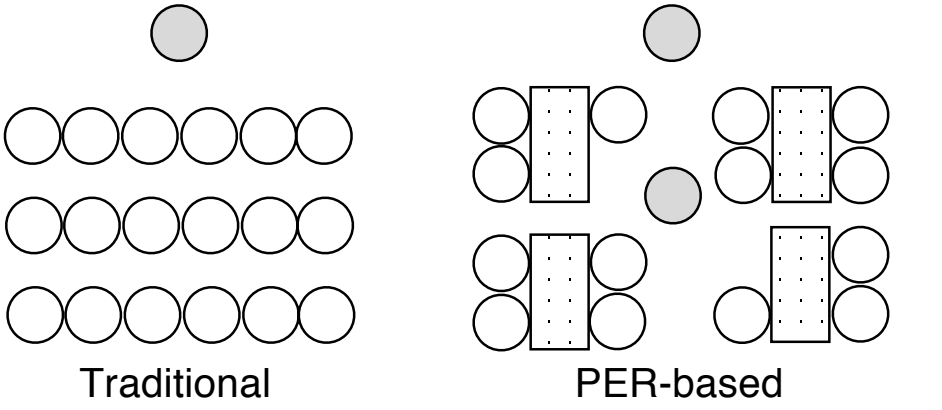


Figure 3.1, Class Layout: Class layout for Traditional and PER-based classrooms

3.1.2 - PER-based Labs

Another source of contextually unique situations at CCNY is the lab section of the introductory physics course. Physics PER-based labs were included with the regular introductory physics labs from 2003 to 2007. Both labs used motion detectors and were specifically designed to encourage group discussions and were based on curriculum that was developed and tested by Sokoloff *et al* (Sokoloff 1999).

The first new lab, called "Motion Detector Lab" (see Appendix for the full lab), was adapted from the Tutorials in Introductory Physics lab (McDermott, 2002). In the

lab, students make predictions for position vs. time as well as velocity vs. time graphs and then perform the motions in front of a motion detector to produce the graphs. The students are encouraged to discuss their predictions with each other and to reach agreement.

The second lab, called the Simple Harmonic Oscillator (see Appendix for the full lab) involves using a mass hanging from a spring and placing a motion detector on the ground beneath the mass. The design philosophy is similar to the one used the "Motion Detector Lab"; students are asked to make predictions and carry out experiments to test them. Student are also asked to design their own experiments to test out the effect of various parameters on the simple harmonic motion of the mass hanging on the spring.

3.2 - Force Concept Inventory

The Force Concept Inventory (Hestenes 1992) was developed to probe student beliefs about Newtonian concepts. Many studies have shown that students enter an introductory physics course with their own set of commonsense beliefs about force and motion (Halloun 1985). Teaching Newtonian mechanics generally involves exposing students to Newton's laws and teaching them how to apply them to solving traditional physics problems.

It has been shown that even after students learn to solve common mechanics problems, they still exhibit beliefs about mechanics that are non-Newtonian. In other words, students often learn to answer typical physics problems but, when probed, they often maintain pre-Newtonian ideas about force and motion (McDermott 1980, 1981 & 1987).

The FCI is a set of multiple-choice questions where the students are forced to choose between a Newtonian concept and common incorrect belief about force and motion. It was rigorously tested and refined during its development. The test is generally given twice to the students, once at the beginning of the semester before instruction and once at the very end of the semester.

The first administration of the FCI is to observe the initial state of students at the start of their undergraduate experience in science. The post-instruction administration permits measurement of effect that instruction has had on student beliefs about force and motion. Two example questions from the survey are shown in Figure 3.2.

25. A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed "vo". The constant horizontal force applied by the woman:
(A) has the same magnitude as the weight of the box.
(B) is greater than the weight of the box.
(C) has the same magnitude as the total force which resists the motion of the box.
(D) is greater than the total force which resists the motion of the box.
(E) is greater than either the weight of the box or the total force which resists its motion.

26. If the woman in the previous question doubles the constant horizontal force that she exerts on the box to push it on the same horizontal floor, the box then moves:
(A) with a constant speed that is double the speed "vo" in the previous question.
(B) with a constant speed that is greater than the speed "vo" in the previous question, but not necessarily twice as great.
(C) for a while with a speed that is constant and greater than the speed "vo" in the previous question, then with a speed that increases thereafter.
(D) for a while with an increasing speed, then with a constant speed thereafter.
(E) with a continuously increasing speed.

Figure 3.2 – Example FCI Questions: Two example questions from the FCI survey

3.2.1 - Test Subjects

The FCI survey has been given to 432 students in 20 sections of traditional and PER-based calculus-based introductory courses from 1999 to 2006. The average class makeup was similar to those reported by Steinberg & Donnelly (Steinberg 2002), where the majority of students speak English as a second language.

The survey was given to students in the PER-based course, the non-PER course, by students who performed PER-based labs and by students who did not use the PER-based labs.

3.2.2 - FCI Results

The Normalized Gain (G_N), as described in Chapter 2, is given by:

$$G_N = \frac{(\text{PostScore\%} - \text{PreScore\%})}{(100\% - \text{PreScore\%})}$$

The results of the FCI are summarized in Table 3.1. All classes showed gains as a result of instruction. There is a difference between the gains in PER-based and non-PER classes, as shown in Table 3.2. The PER-based classes score significantly higher gains than the traditional classes; this is consistent with the results reported by Hake's survey of over six thousand students in high school and undergraduate classes (Hake 1998).

Figure 3.3 shows a Hake plot of all of the FCI data, comparing PER-based classes with traditional classes. A Hake plot has pretest percentage on the x-axis and percent gain on the y-axis. When plotted this way, the line that goes through (100,0) represents equal values of the fraction of the possible gain. The topmost line shows the maximum possible fractional gain for each given pretest score. Two such lines are plotted for each

of the two groups of data; to show the upper and lower bounds. The PER-based classes' percent Gains range from 32 to 59, whereas the remainder of the classes have percent Gains that range from 5 to 29. These results are nearly identical with national norms as reported by Hestenes and Hake (Hestenes 1992, Hake 1998).

		New Labs		Lecture Type		Normalized
Semester	**N**	**1D**	**SHO**	**Trad.**	**PER**	**Gain**
Fall 99	45				x	0.43
Fall 99	38			x		0.23
Fall 01	16				x	0.40
Fall 01	17			x		0.17
Fall 01	14			x		0.08
Fall 01	14				x	0.44
Fall 02	18	x			x	0.49
Fall 03	9	x		x		0.24
Fall 03	9	x		x		0.24
Fall 03	30	x			x	0.29
Spring 04	17	x		x	x	0.15
Spring 04	17	x		x		0.17
Spring 04	37	x			x	0.37
Fall 04	28	x			x	0.51
Fall 04	9	x		x	x	0.06
Fall 04	22	x			x	0.40
Spring 04	29	x	x		x	0.32
Fall 05	28	x	x		x	#N/A
Spring 06	35	x	x		x	0.32

Table 3.1 List of all CCNY FCI Data: Classes that were given the FCI (N = 432) with indications of which type of instruction or lab they had.

N = 432	Average Gain
PER	0.37
Traditional	0.17

Table 3.2 FCI Gain: Average FCI Gain broken down by class

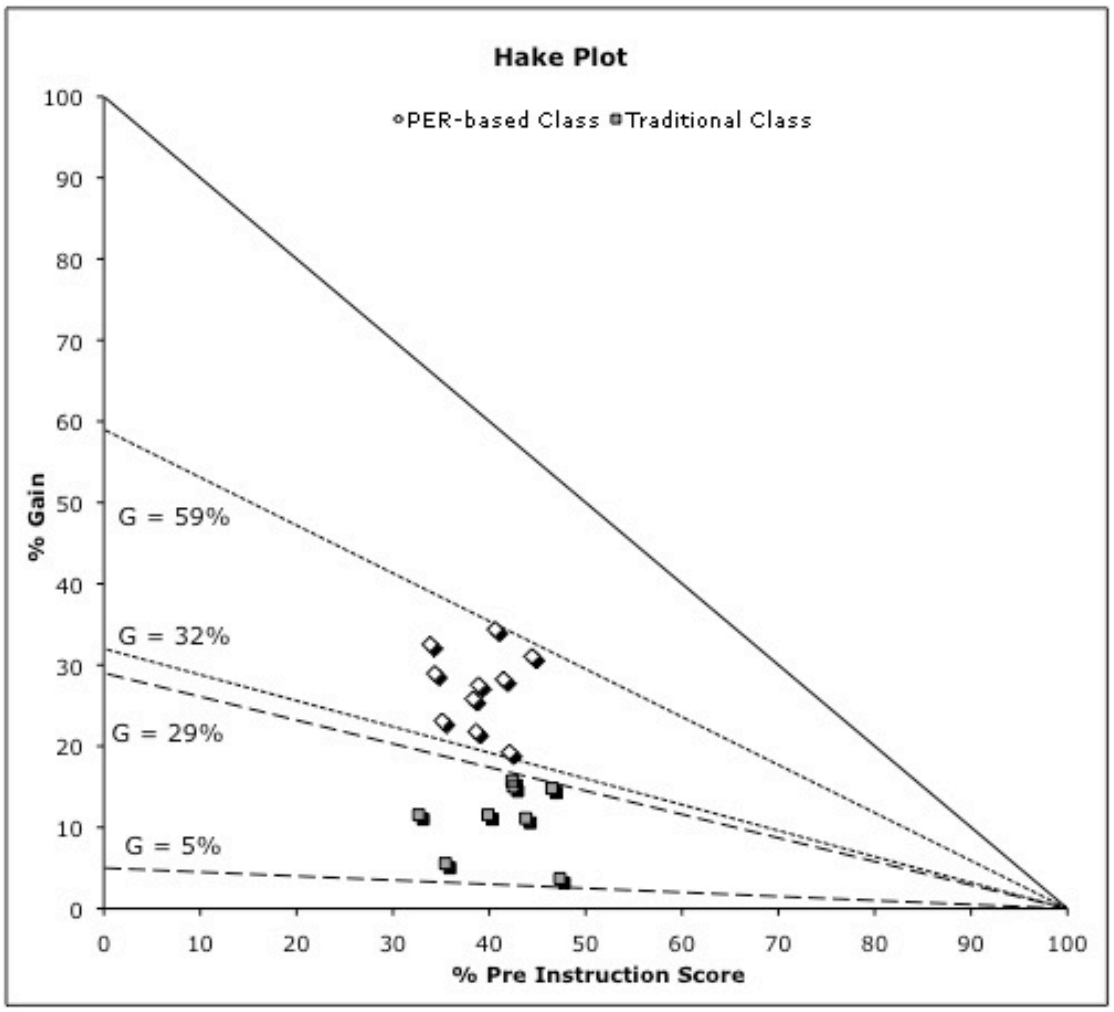


Figure 3.3 Hake Plot of all CCNY Data: Average FCI Gain broken down by class type and Lab type. PER-based class scores are bound by lines of equal % Gain from G = 59% to G = 32%. Non-PER classes are bound by lines of equal normalized Gain from G = 29% to G = 5%.

3.3 - Lab Videos

Our second investigative tool was the analysis of videotapes of students performing the introductory physics course labs. We videotaped students working on group tasks in class and doing labs together in their lab section. A camera and microphone were placed near the experimental apparatus so as to not interfere with the students. We recorded them over the entire lab period of two and a half hours.

3.3.1 - Rubric

In order to quantify the differences between the two labs, it was decided to investigate how the students spent their time on different activities while doing either regular labs or PER-based labs. The goal was to find a quantitative measure of what the students do during the two lab types to see if there was a significant difference.

It was decided to formulate a time code rubric, which could be used to break down how the students spent their lab time into several different activities. Observing several of the videotapes made evident the kinds of activities that students perform during a lab. A list was made of the most common activities. The list was then refined, removing items that seemed to be duplicated by other items. The goal was to use as few codes as possible but not lose any information about their activities. After several iterations the code was finalized and is shown in Table 3.3.

The activities deemed most likely to promote student discussions were determined to be Model Based Reasoning, Experience Based Reasoning, and Peer Instruction.

Code Name	Description
Calculations	Students is calculating values using a formula.
Performing Experiments	Student is performing the experiment.
Reading	Student is reading the lab instructions.
Data Logging	Student is writing down the results of the experiment.
Teacher Instruction	Teaching Assistant is showing student how to perform experiment or answering questions.
Nothing	Student is doing something not associated with the experiment.
Model Based Reasoning	**Student is attempting to make sense of the situation using a physical model.**
Experience Based Reasoning	**Student is attempting to make sense of the situation using reasoning based on own experiences.**
Peer Instruction	**One student is explaining their understanding of the situation to another student.**

Table 3.3 – Coding Scheme for Lab Rubric: Coding scheme for the rubric for the videotapes of students performing labs, activities that are more expert-like are shown in **Bold**

We first tried to use a very detailed time code, assigning one of the rubric codes to every second of the time spent on the lab. This proved to be very time-consuming and perhaps unnecessary. It was then decided to try to break the time into 30-second packets and assign a code to each packet.

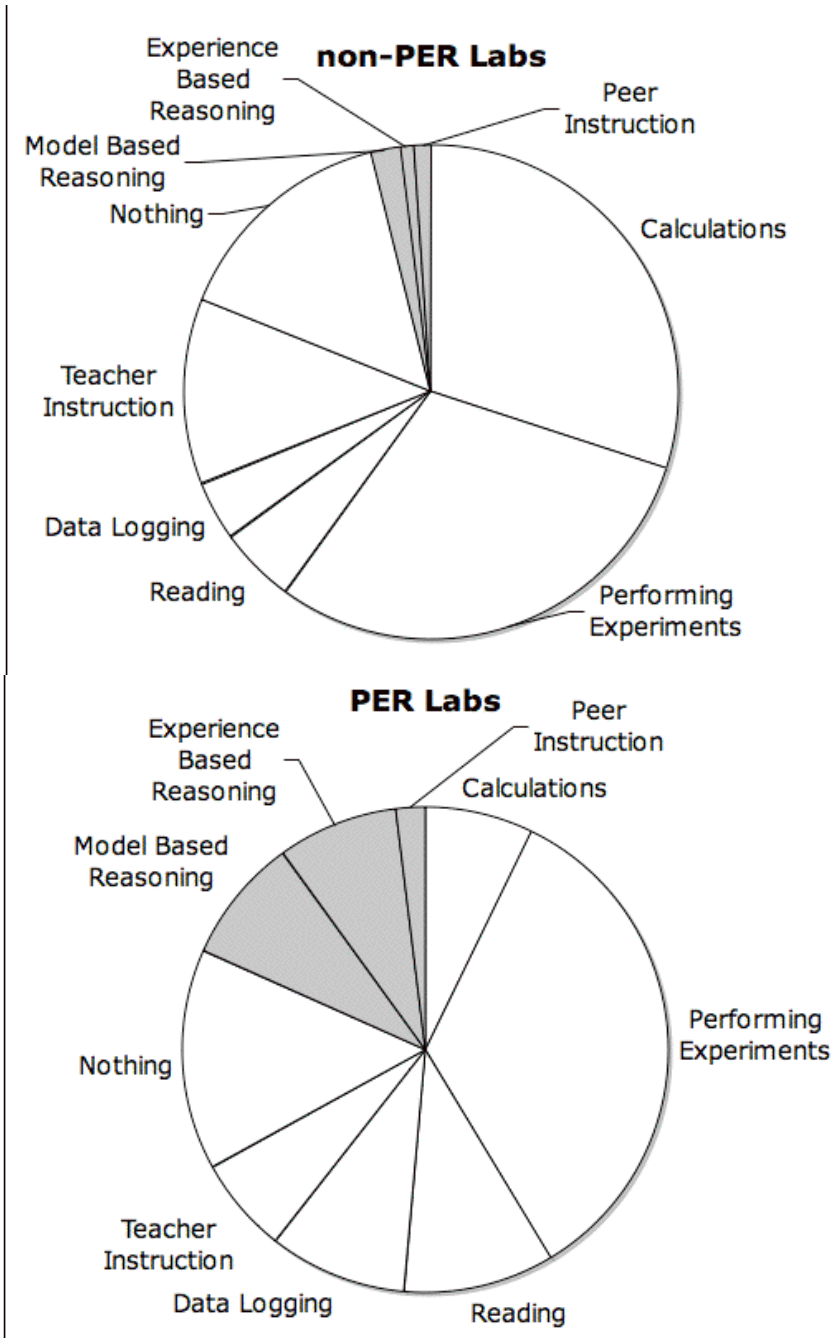
Each successive 30-second packet would receive on of the codes for the activity that the student spent most of their time on. We tried the 30-second packets and the second by second approach to the same 10-minute clip to see how they compared and found the results to be very similar.

We proceeded to use this 30-second packet system to code two sessions of students performing the new labs and two sessions of students performing the traditional labs.

3.3.2 - Results

The results of the coding are summarized in Figure 3.4. It is a breakdown of the different activities the students spent their time performing during the lab period. The students performing the PER-based labs spent about 20% of their time undergoing what were considered epistemologically productive activities; the student in traditional labs spent only about 4% of their time on the same activities.

Figure 3.4 Lab Rubric Results: Results of lab rubric applied to videotaped labs. Time spent is shown for both the old labs and the new PER-based labs. The epistemologically productive activities are darker. The PER-based labs have the students spend 18% of their time on epistemologically productive activities whereas the traditional lab had the students spend 4% of their time on those activities.



3.4 - Summary

Students taking introductory physics classes at CCNY are immersed in a variety of unique contexts, they study in a multicultural environment, they take PER-based and non-PER courses, and both PER-based and non-PER labs. The FCI results show that the PER-based classes did have a strong positive impact on student understanding of the concepts in dynamics. These results are consistent over several classes over a long time frame and are very robust.

The lab time code analysis shows that PER-based curriculum affects more than just conceptual understanding. The students in the new labs were interacting in a different way than students in other labs. A larger percentage of their time was spent on reasoning and peer instruction activities.

The various aspects of a multicultural classroom, meaning different cultures and native languages of the students, did not prevent the PER-based curriculum from improving student conceptual understanding.

CHAPTER 4 - Special Relativity: Investigating Twin Brothers Solving Problems in a Difficult Subject with no Classical Foundation

"In my soul, I really feel that God has one big clock on which all events are registered. However, intellectually, I know that electromagnetism, the full equivalence of all inertial observers, and the reports of experiments do not agree with this point of view, so that I carefully sort out the behavior of systems in each inertial frame."

-Anonymous physics professor, 2006

4.1 - Introduction

Studies of difficulties students have with classical mechanics have shown that many students display a disconnection between the theory and its application to everyday situations (McDermott 1980 & 1981). For example, when asked to consider a box being pushed, many students conclude that a force is required to keep an object in motion. Everyday situations lead students to believe that force on an object is proportional to its velocity. New curriculum has been developed that successfully helps students understand that force is proportional to acceleration and not velocity (McDermott 1996). This curriculum works by having students tie the theory to everyday situations and has been shown to be very effective in helping them develop a deeper conceptual understanding of force and motion.

Now consider special relativity, where the concepts cannot be so easily related to everyday experiences. It is easy to think about forces by considering a box being pushed on the floor but there is no equivalent situation for special relativity. The situations one must consider are far removed from everyday experience, for example: " Please consider

Philippe standing by a train track and a train is approaching him at 80% of the speed of light…"

There is an added level of abstraction since the velocities needed to see relativistic effects are much larger than those encountered in everyday life. Techniques that worked for classical mechanics cannot work the same way here. These further difficulties for teaching also provide new and interesting possibilities for the researcher.

We had a unique opportunity to perform a controlled experiment on this material: a chance to interview identical twin brothers working together to resolve the twin paradox. These were two intelligent and articulate students with similar backgrounds but with diverging undergraduate experiences. They were asked to tackle an incredibly difficult special relativity problem. The brothers attended very different physics classes: one happened to take traditional classes and the other happened to take classes designed through PER.

In these interviews, we saw evidence of how the brothers' epistemologies differ, and how that affected their ability to solve these particular kinds of physics problems. We present some excerpts from the interview that highlight the positive effects PER-based special relativity curriculum has had on one brother's approach to making sense of an unfamiliar problem.

4.2 - Twin Paradox Interview

4.2.1 - The Twin Brothers

The subjects of the study were identical twin brothers whom we will call Fred and George. Both studied science and were smart and successful students. They excelled in all of their science classes and both later went to prestigious graduate schools.

One important difference between them is that Fred's physics courses were all PER-based, whereas George took traditional courses. Fred took two introductory physics courses and a modern physics course that used special relativity tutorials developed by the University of Washington (unpublished, private communication). In particular, the modern physics tutorials included a tutorial specifically designed to "elicit, confront & resolve" student difficulties with relativity of simultaneity. One of the tutorials explicitly dealt with relativity of simultaneity, one of the consequences of special relativity. On the other hand, all of George's physics courses were entirely traditional; they were based around lectures and included no tutorial sessions.

This was a situation with identical twin brothers with similar backgrounds but with divergent college level science experiences. An investigation of this situation will be able to explore how Fred's exposure to the PER-based physics curriculum not only influenced his ability to resolve special relativity problems, but also his beliefs about science as compared to his traditionally instructed brother.

Fred and George were seated together and asked to resolve a version of the twin paradox problem as we videotaped them. They were given a calculator, some paper and a modern physics textbook. Neither of them knew ahead of time what kind of problem we would be giving them. We encouraged them to work together and openly discuss their answers. The brothers expressed themselves clearly and participated equally and enthusiastically in the lively discussion that followed.

4.2.2 - The Twin Paradox

> *"... according to Dr. Hasslein's theory of time in a vehicle traveling at close to the speed of light, old Mother Earth has aged a few thousand years since our departure -- while we have scarcely aged at all. It may be so. This much is probable: the men who sent us on this journey have long since been moldering in forgotten graves; and those, if any, who read this message are a different breed. Hopefully, a better one."*
>
> *-Colonel George Taylor, Planet of the Apes (1968)*

The version of the Twin Paradox problem presented to Fred and George is summarized in Figure 4.1 and shown in full in the Appendix. They were asked to calculate the amount of time elapsed for the outbound and inbound legs of Bonnie's trip as measured by Aaron and by Bonnie.

To resolve the problem, the students would first need to calculate the time elapsed for Aaron according to Aaron by using the definition of velocity. The next step would be to calculate the time elapsed for Bonnie according to Aaron by application of time dilation.

Students should then recognize that, from Bonnie's point of view, the distance between the planets is smaller due to length contraction. She would then calculate the time elapsed for her based on this new distance and then apply time dilation to calculate the time elapsed for Aaron.

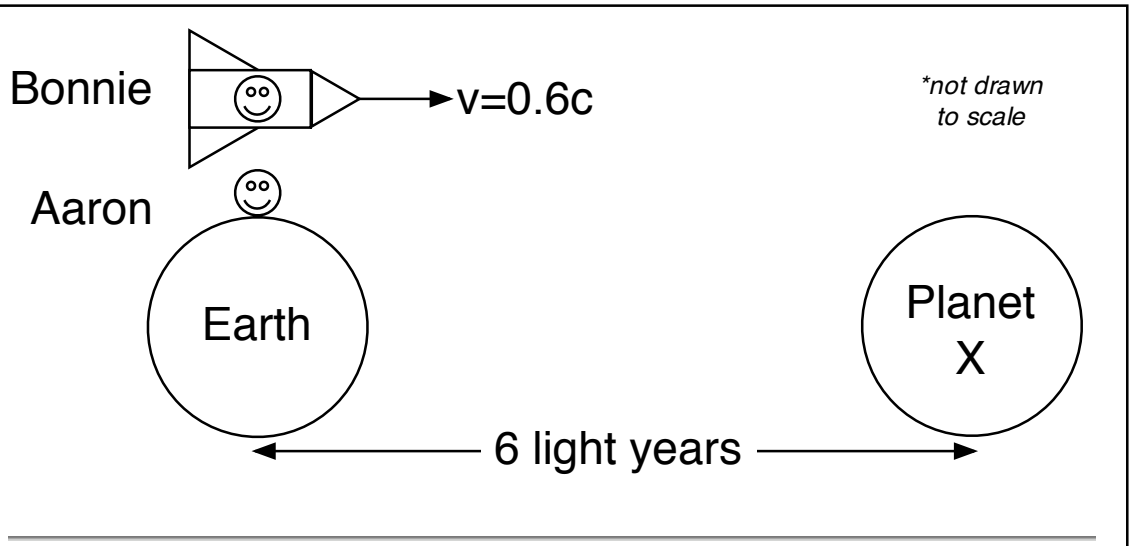


Figure 4.1 - Twin Paradox Question: Bonnie flies to Planet X and returns to Earth at a constant velocity while Aaron stays on Earth. By application of special relativity, determine who is older: Aaron or Bonnie

There is an apparent conflict between the travel times for Aaron as calculated by Aaron and by Bonnie (calculation results are shown in Table 4.1). Each twin correctly calculates a different travel time for Aaron for each leg of the trip. However there is a breaking in the symmetry between the two points of view: when Bonnie turns around at Planet X, she switches reference frames through acceleration.

According to	Time passed for	Outbound (years)	Inbound (years)	Total (years)
Aaron	Aaron	10	10	20
	Bonnie	8	8	16
Bonnie	Bonnie	8	8	16
	Aaron	***6.4***	***6.4***	***20****

Table 4.1 - Twin Paradox Resolution: The calculation of time for each leg of the trip according to each observer. Aaron's total time is more than the sum of both legs due to Aaron changing reference frames at Planet X. There is no paradox as both twins agree on how much time the other took for the trip.
* This accounts for changes to Aaron's clock as seen by Bonnie

Bonnie would observe Aaron's clock running very quickly during her turnaround time. Accounting for this asymmetry, the correct conclusion is that Aaron ages 20 years and Bonnie ages 16 years.

Another way to understand the resolution of the twin paradox is to look at Planes of Simultaneity (depicted in Figure 4.2). Any events on a given dashed line are simultaneous in that particular reference frame (on the left: they are simultaneous in Aaron's reference frame, on the right: in Bonnie's reference frame). The planes for the rocket change alignment when the rocket changes reference frames. At that turnaround point, the plane's intersection with the Earth timeline jumps ahead, corresponding to a large amount of time passing for Aaron as Bonnie turns around at Planet X.

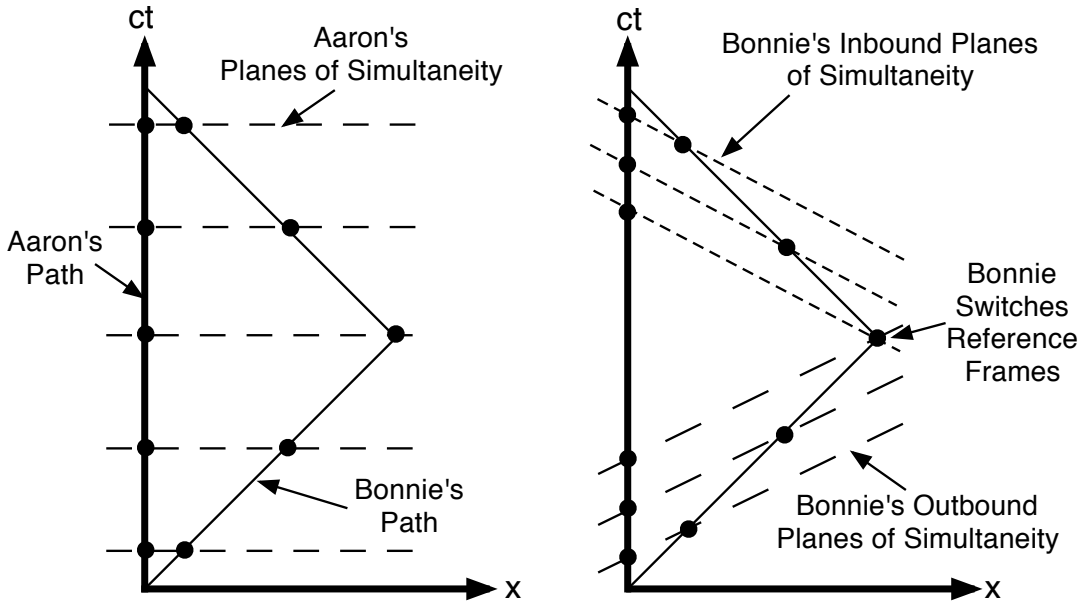


Figure 4.2 - Space-time Diagram of Twin Paradox: Space-time diagram in Aaron's reference frame with simultaneity planes drawn for Aaron and for Bonnie. The dashed lines for each graph go through events that are simultaneous. Notice the discontinuity in the planes for Bonnie at the turnaround point.

We did not expect the brothers to have enough familiarity or experience with special relativity to recognize this asymmetry and to be able to give a complete resolution to this problem. We presented this problem in order to see how their different educational experiences affected how they would try to resolve something unfamiliar and challenging. In other words: how will Fred, who did many PER-based activities, approach the problem differently than George?

4.2.3 - The Interview

Here we describe the process that the brothers went through as they calculated their results. We will show and discuss representative quotes from the brothers that highlight their different approaches and the reasoning they applied.

Fred and George first worked out the times as calculated by Aaron for the first leg of the trip. They used the definition of velocity to find the time passed for Aaron, and correctly applied time dilation to calculate the time passed for Bonnie. This was a straightforward calculation with which both students were comfortable. They both agreed that according to Aaron for the first leg of the trip, Aaron's clock should read 10 years and Bonnie's clock should read 8 years.

The next step was for them to find the times for the first leg of the trip as calculated by Bonnie. Before they even tried to calculate it, they argued over what the answer should be. George believed that Bonnie's results should be the opposite of Aaron:

> **Fred:** Now we're changing frames...but the answer is the same.
>
> **George:** No!...there's no symmetry.

Fred's intuition seemed to suggest that the clock reading should be whatever it is regardless of who is reading it. George believed that since Aaron calculated 10 years for himself and 8 years for Bonnie, Bonnie should get the opposite: 10 for herself and 8 for Aaron. In the following excerpt, Fred explained this result:

Fred: The fact is that it will take less time for her to reach it. So if we go from his frame it takes 10 years, for her now it should take less because this [Planet X] is closer.

George: Well I know that but uh, I'm disturbed by it.

Fred: You're disturbed by it?

George: I am bothered by it, because I remember working with like the problems about trains and all that. No frame is absolute.

George was unable to explain his objections properly to Fred's explanation. He used the expression "no frame is absolute" to justify his objections, a phrase he may have heard before, but applied in the wrong context here.

Fred was eventually able to convince George to calculate the time based on the contracted distance that Bonnie would see and they found the correct result of 8 years.

Next, they tried to calculate the time passed for Aaron according to Bonnie. Fred immediately noticed that Aaron's clock will run slow according to Bonnie and that Bonnie will calculate that the time for him will be 6.4 years. He started to argue that the result of 6.4 didn't make sense:

Fred: So Aaron tells you my clock says 10 and then Bonnie's goes and she says no: Aaron's clock says 6.4. How on earth [author

note: no pun apparently intended] can they have 2 different times if it's the same, if it's the same clock? How can they measure 2 different things?

George: It's the answer.

Fred: No! Something is terribly wrong

Even in this difficult problem, Fred was concerned that there was an apparent conflict with real world expectations when they tried to put all the numbers together. He was confident that they had applied the theory properly to calculate the times for each leg of the trip, but he believed that there must be something missing when they put it all together. On the other hand, George was willing to accept the result of the equation.

Fred and George were unable to resolve the difference in calculated times for the outbound leg of the trip. At one point, Fred considered that the difference might be resolved by considering the simultaneity of events:

Fred: If you do the coordinate [transformation], the events are reaching the planet and looking at the clock... ... it's not simultaneous.

Fred approached the problem from a different point of view. He tried thinking about the simultaneity of the events to see if this was relevant, hence demonstrating an understanding of the relativity tutorials that he had been through. Unfortunately this thread of the discussion was brief.

Throughout the discussion, Fred tried to resolve conflicts by discussing why a certain equation was applied and whether or not it was the appropriate approach. George spent more time double checking their calculations and leafing though the modern

physics textbook (at one point he reached for the textbook saying "Let's put some order in this chaos."). Nevertheless, they were both unable to successfully resolve the paradox.

Near the end of the session, referring to the reunion of Fred and George, the interviewer asked them about the conflicting total times:

> **Interviewer:** Do these 2 numbers have to be the same: Aaron's clock according to Aaron and Aaron's clock according to Bonnie?
>
> **George:** No.
>
> **Interviewer:** ...Why 'no'?...
>
> **George:** That's what relativity is.

George eventually came to think that relativity just has this problem built into it. He was willing to accept that there is no resolution and gave up on the possibility that there could be a resolution to this apparent conflict whereas Fred clearly recognized that when Aaron and Bonnie meet they need to agree on the times and which of them is older.

4.3 - Other Interviews

All of the interviews with the brothers can be broken down into the two following groups:

1. Working together on the following physics problems
    - Twin paradox interview
    - Pendulum problem
2. Working by themselves on the following problems
    - 2-D mechanics problems: Rifle bullet and dropped balls
    - Photoelectric problem

- Lorenz transformation
- Potential problem: Classical & Quantum

A review of the videotapes of those interviews revealed several instances of Fred or George displaying approaches similar to those found in the Twin Paradox interview. Representative clips from three of the interviews are shown in Figures 4.4, 4.5, and 4.6.

Excerpt 1

Interviewer: "Why does a particle bounce back at this point? [Classically]"

Fred: "it's moving at constant speed then reaches potential and experiences a force"

Excerpt 2

George: "...I don't know... I think of a potential like a wall"

Figure 4.3 - Potential Interview Excerpts: Representative Quotes from the Lorentz Transformation interviews

Excerpt 1

Fred: "I want to convert the light to energy, I want to see if I can get away somehow without having to use a formula"

Excerpt 2

George: "I don't know, I didn't do it in class now that I think about it"

Excerpt 3

George: "If I increase the potential the e- will stop flowing"

Interviewer: "Why?"

George: "Because I'm increasing the potential"

Figure 4.4 – Photoelectric Effect Interview Excerpts: Representative Quotes from the Photoelectric Effect interviews

Excerpt 1

Fred: "I'm trying to visualize it because I don't want to plug it in blindly"

Excerpt 2

Fred: "I feel guilty just popping in numbers not knowing what they are"

Excerpt 3

George: "this is sad, I'm just plugging in numbers"

Figure 4.5 - Lorentz Transformation Interview Excerpts: Representative Quotes from the Lorentz Transformation interviews

Their responses in these interviews are consistent with the analysis of the Twin Paradox interview. Fred demonstrates more willingness to question his results whereas George will more easily fall back on referring to results from class or other authority. The differences in their approaches are present in interviews where they worked alone as well as the ones where they worked together. In the photoelectric effect example, Fred tried to avoid having to depend on formulas; he wanted to reason through the problem instead. George does show some circular reasoning in the photoelectric effect excerpts, but in the Lorentz transformation interview he is at least able to recognize that he is just using formulas without understanding them

4.4 - Rubric Analysis

In order to support the findings of the qualitative analysis of the transcripts of the interviews, a rubric was developed to measure if there was a measurably different approach between the brothers to solving problems. The final rubric is shown in Table 4.2.

	Code Description	Example Statement
A (Expert – Like)	Student uses epistemological approaches consistent with that of an expert. This includes statements indicating that the student: **a.** stresses understanding of underlying ideas and concepts, **b.** believes that science is a connected consistent framework **c.** takes responsibility for constructing their own understanding	**a.** -"We need to think about what this means." - "Why does this imply the time should be shorter?" - "That can't be right." **b.** - "Shouldn't the result from energy conservation coincide with this result?" - "That formula gives one answer, why does the other not give the same?" - "That's like what happens in a gravitational field." **c.** - "I'm trying to figure out how this works." - "I'm not blindly accepting those results." - "Why is this result less than expected?"
B (Novice – Like)	Student uses epistemological approaches consistent with that of a novice. This includes statements indicating that the student: **a.** focuses on remembering and using formulas **b.** believes science can be treated as unrelated facts **c.** takes what is given by authorities without evaluation	**a.** - "I'm trying to find the equation that fits." - "Those variables all fit into this equations so we should use this one." - "We just need the right formula for that." **b.** - "That's what the formula gives us so it's correct." - "I try not to think about the big picture." - "All we need here are equations of motion." **c.** - "Its right because it's special relativity." - "Because that's what the formula says." - "Where is that in the book?"

Table 4.2 - Twin Paradox Interview Rubric: Rubric designed to classified as student statements that are expert-like or novice-like.

The rubric was applied to the transcript of the twin paradox interview. The Results are summarized in Figure 4.3 and 4.4. We see quantitative confirmation that Fred's approach is much more Expert-like than George's. Of the classifiable statements coded, 50% of them were expert-like for George and 94% of them were expert-like for Fred. This is consistent with the qualitative analysis of the transcript performed in section 4.2.

	Fred		George	
	Expert-like	**Novice-like**	**Expert-like**	**Novice-like**
Twin Prdx	94%	6%	50%	50%
Pendulum	86%	14%	40%	60%
Potential	87%	13%	46%	54%
Average	***89%***	***11%***	***45%***	***55%***

Table 4.3 - Interview Rubric Percentages: The results of the rubric applied to three interviews, broken down by percent.

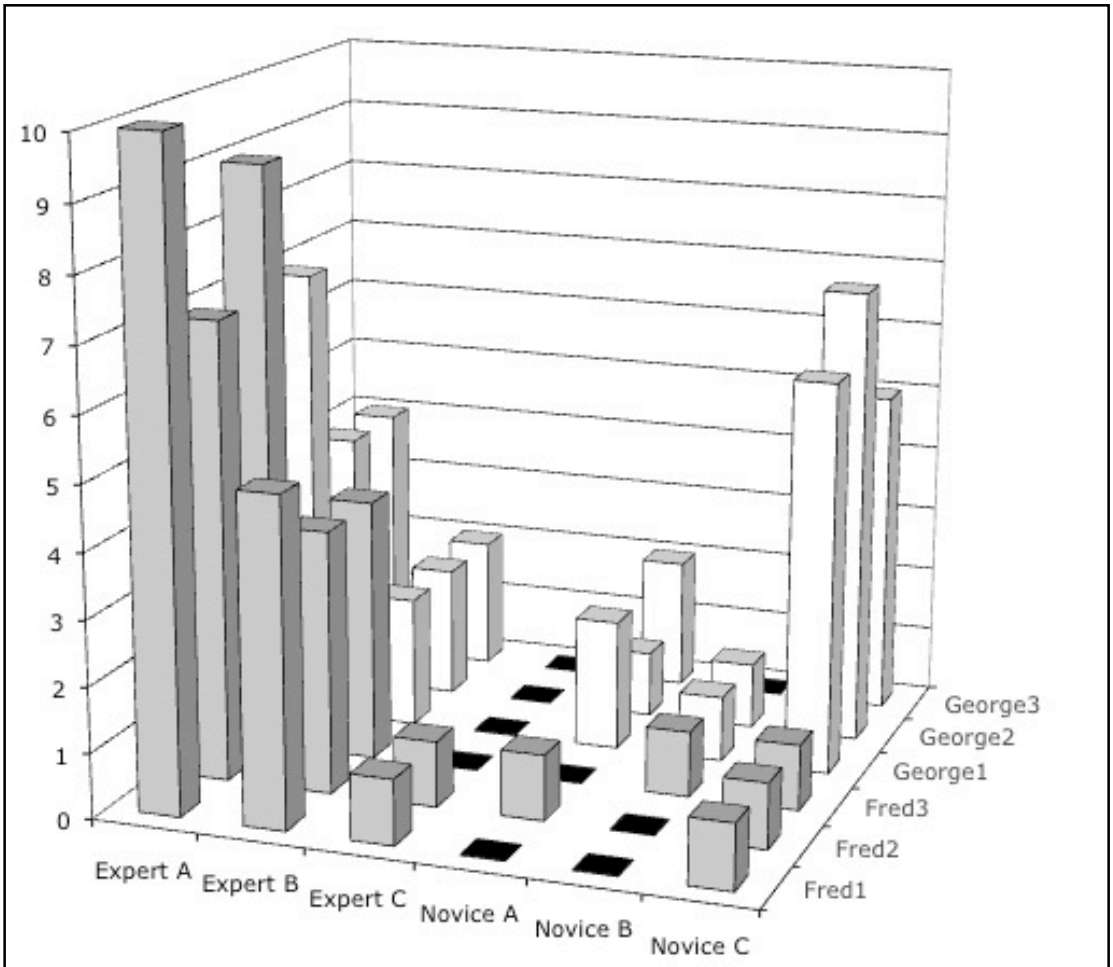


Figure 4.6: Twin Paradox Rubric Counts: Plot of the number of statements made by Fred & George in three interviews for each of the Novice and Expert Categories. The interviews are 1) Twin Paradox, 2) Pendulum, and 3) Potential.

4.5 - Summary

We observed two intelligent students struggling in the context of the counter-intuitive twin paradox problem, which is so difficult that many graduate students often have difficulty resolving it. We were able to explore how two students with similar backgrounds, but with very different physics learning experiences, approach trying to solve the problem. The students' educational experiences had a significant impact on how they approached the problem.

George's approach was to look for the correct equation, calculate the result, and then to find ways to justify the answer he found. The fact that a result was physically impossible for the twin paradox did not deter him. He assumed it was a result of special relativity.

Fred, who in his physics courses was often encouraged to discuss and develop his ideas out loud with his peers, would question any result they found and would try to make sense of it. He showed greater understanding of underlying concepts and his thinking is more consistent with a student who has a more expert approach to the nature of learning.

The additional interviews with Fred and George permitted us to verify the validity of the results of the Twin Paradox interview by looking at their work in different situations. The interviews covered situations where they were working on classical and modern concepts as well as where they were working alone and together. As shown in the analysis, they displayed similar approaches to those used in he twin paradox interview: both brother trying to solve the problems in different ways.

These qualitative observations are supported by the rubric analysis of the twin paradox interview, the pendulum interview and potential interview. The brothers' statements are consistent: George had a more novice-like approach and Fred had a more expert-like approach.

This case study of identical twin brothers highlights the impact that PER-based activities can have on both student conceptual understanding and epistemology. Even though both brother were ultimately unable to resolve the twin paradox, we saw that Fred's approach was much more flexible and productive than George's.

CHAPTER 5 - Conclusions

I once spent a week training teachers in the Mabaruma district in the rain forests of Guyana. I was asked to give them an overview of a variety of scientific concepts of my choice, something that they could bring back to teach at their schools.

On the first day, I presented something I thought would be very interesting; magnetism. Despite my diligent preparation and including many demonstrations the teachers where unimpressed and lost interest in the material early on. The next day I tried the theory of gravity and this was failing just as badly at the start. It was only when I mentioned how gravity is related to the tides that my class perked up and finally became interested. They had so many questions that I had to spend the entire next day elaborating on tides.

It turns out that crab fishing, which is highly dependent on the tides, is a major part of the local economy. The material only struck home with the student when it became relevant to them and their students' lives. More difficulties arose from cultural differences and language barriers because they spoke Guyanese Creole English.

When I first started learning and using PER-based curriculum at CCNY, I remembered this experience in Guyana. The Guyanese teacher class, for all the difficulties that arose, was at least a relatively homogeneous group. A physics class at CCNY is much more complex than the Guyanese teacher class, since it presents multiple cultural or language barriers within a group of students hailing from all around the world. The barriers complicate the situation even more when it comes to PER-based curriculum

since it requires a lot of interaction between the students working in groups to solve problems together.

Our investigations studied learning environments that were contextually rich and diverse beyond the multicultural and PER-curriculum aspects. Our subjects were studying a wide variety of subject matters: introductory calculus-based physics, astronomy, and special relativity. The level of the students included high school students, undergraduates and pre-service teachers with undergraduate degrees. There were even differences in the basic design philosophy of the curriculum that was studied: some of it was designed to effect improved conceptual understanding and some directly targeted student attitudes about the nature of doing and learning science.

A superficial assessment of the results of our investigations reveals some initial conclusions about the use of PER-based curriculum at CCNY. We found that the curriculum was able to improve student conceptual understanding of subject matter in introductory and modern physics. We also showed that it is possible to positively change student epistemology, i.e. their approaches to learning and doing science, with curriculum specifically designed to do so. Finally, we showed that change was possible in both conceptual understanding and epistemology even when used with the counter-intuitive subject of special relativity.

Bringing all this information together, we are able to make a deeper statement about these conclusions: All of the different curricula were designed and implemented with the given results in mind but it is the fact that it was successful in such a wide diversity of environments that is unique. Ultimately, this thesis showed that PER-based

curriculum overcame a wide variety of contextual influences to positively impact student learning and epistemology.

These results suggest interesting opportunities within Physics Education Research. There are potential barriers to the success of interaction-based curricula from many sources of contextual complexity. Advanced physics concepts, for example, rely on a more complex and abstract mathematical framework than introductory physics, which may be difficult to incorporate into an interactive classroom environment. The findings suggest that it is possible to develop successful PER-based material not only for science classes for mature students or non-native English speakers, but also for advanced physics education.

Appendix A.1 – High School Data

		MPEX										Teach	Earth-Sun				Black Hole		
				Pre				Post				Eval		Pre		Post			
Year	ID	R	I	Coh	Con	Avg	R	I	Coh	Con	Avg	Avg	#	text	#	text	#	text
2005	1	3.3	3.8	3.2	4.3	**3.4**	4.0	4.0	3.4	4.0	**3.8**	**4.3**	B 1	According to Cop	B 4	Before Newton's L	D 5	If I hadn't taken this c
2005	2	5.0	4.2	3.8	3.3	**3.9**	4.0	3.8	4.0	3.7	**3.9**	**2.3**	B 1	We know that sur	B 3	Earth goes around	D 4	I do not know because
2005	3	4.0	3.8	3.8	3.5	**3.7**	4.5	3.5	3.2	3.3	**3.6**	**3.0**	B 1	The sun is the ce	D 3	Both A and B are t	D 4	I don't know because
2005	4	4.0	3.8	3.4	4.0	**3.6**	3.8	3.8	3.6	4.0	**3.7**	**3.2**	B 1	The earth goes a	D 5	The relative motio	D 4	I don't know whether
2005	5	4.5	3.8	3.0	4.0	**3.6**	4.3	4.0	3.4	4.0	**3.8**	**3.7**	D 3	I don't know, in s	B 4	B, the earth goes	D 3	Based on the knowled
2005	6	3.8	3.7	4.4	3.0	**3.8**	4.0	4.2	4.2	3.7	**3.9**	**3.8**	B 2	The sun has mas	B 2	To tell you the trut	D 4	I have hear of the terr
2005	7	4.5	4.5	4.2	4.7	**4.2**	4.8	4.0	4.4	4.0	**4.2**	**4.3**	B 1	The sun acts as a	D 4	Many people once	D 5	Not a lot is know abou
2005	8	4.0	3.7	3.0	3.7	**3.5**	3.3	2.8	3.0	2.0	**2.8**	**2.0**	C 1	The earth goes a	B 1	I say B because th	D 3	I choose D because I c
2005	9	5.0	3.7	3.8	3.7	**4.3**	4.0	4.5	4.0	5.0	**4.5**	**1.7**	B 1	Well the earth mo	B 3	The earth goes arc	D 5	I don't really know if t
2005	10	4.3	4.0	4.2	3.7	**3.9**	3.8	4.0	3.8	3.7	**3.9**	**3.5**	B 2	The earth goes a	D 5	Since the question	D 4	I did not learn this in c
2005	11	4.0	4.3	3.0	4.0	**3.6**	4.8	4.0	3.4	4.0	**3.9**	**3.2**	B 1	The Earth Planet	D 3	If I work with a m	D 4	I cannot tell which sta
2005	12	5.0	5.0	4.6	5.0	**4.8**	5.0	4.3	4.0	4.7	**4.5**	**3.6**	B 1	If the sun were to	B 3	In both geocentric	D 5	If black holes are, as t
2005	13	4.8	3.8	3.4	4.7	**3.9**	4.3	3.2	2.8	3.3	**3.2**	**4.3**	B 1	As far as my kno	D 3	Over the past 6 w	D 4	Since I myself have no
2005	14	4.5	4.0	3.2	3.3	**3.5**	4.3	4.3	3.2	4.3	**3.8**	**2.8**	B 2	I believe the sun	B 3	The heliocentric m	D 3	I do not know which o
2005	15	4.5	4.3	3.8	5.0	**4.2**	4.8	4.7	4.0	4.7	**4.5**	**3.3**	D 2	As it is usually kn	D 3	In our class, we m	D 4	First of all, I can't reall
2005	16	4.8	3.8	4.2	3.0	**4.2**	4.8	4.3	4.6	3.7	**4.5**	**3.7**	B 2	The earth revolve	D 4	It is an observed f	D 3	--statement a is state
2005	17	4.3	3.2	3.2	3.3	**3.5**	4.0	3.3	3.2	3.0	**3.2**	**4.1**	B 1	The year and the	D 3	In the model wher	D 4	Over the course of my
2005	18	4.3	4.3	3.8	4.0	**4.0**	4.0	5.0	4.6	5.0	**4.6**	**4.0**	B 2	We have the noti	B 4	I think B would be	D 5	The existence of black
2005	19	4.5	2.8	3.2	2.3	**3.3**	4.3	3.8	3.8	4.0	**3.8**	**4.1**	B 2	The sun is heavie	B 5	We observed that	D 4	I have not observed a
2005	20	4.3	3.2	3.6	2.3	**3.4**	4.5	4.3	3.2	4.0	**3.9**	**3.3**	B 1	During the year,	B 1	I think B best app	D 5	I think A is most accu
2006	21	4.5	4.0	3.6	4.0	**3.8**	4.5	5.0	4.0	5.0	**4.5**	**4.3**	B 1	The sun is the ce	D 4	I think that we are	D 4	I do not know what th
2006	22	3.3	3.5	3.0	3.3	**3.2**	4.0	3.3	3.2	3.0	**3.5**	**3.3**	B 2	The earth is cons	B 5	The earth goes arc	D 4	Although I have heard
2006	23	4.3	3.8	3.2	4.0	**3.6**	4.0	4.0	3.6	4.0	**3.8**	**4.9**	B 2	The sun pulls the	D 2	According to the o	D 1	According to books wr
2006	24	4.3	3.7	3.0	3.0	**3.4**	4.5	4.8	3.6	4.7	**4.1**	**4.3**	B 1	Since we call it th	B 4	The earth goes arc	D 3	I do not know the ans
2006	25	4.8	4.2	4.2	4.3	**4.1**	4.0	4.5	4.2	4.0	**3.9**	**2.4**	B 1	The heliocentric t	B 5	Based on our obse	D 5	We do not know wheth
2006	26	4.8	3.5	3.8	3.3	**3.9**	5.0	4.7	4.0	5.0	**4.5**	**4.3**	B 1	The sun is in the	B 5	Although I am not	D 5	I do not know which o
2006	27	4.5	4.7	5.0	5.0	**4.6**	5.0	4.7	4.8	4.7	**4.6**	**3.1**	B 1	The sun is the ce	B 3	There have been a	D 3	Although there have b
2006	28	5.0	3.3	3.4	3.0	**3.4**	4.8	3.0	3.0	2.7	**3.1**	**3.3**	B 1	The sun is a mot	B 5	I believe that the	D 1	I am not really too far
2006	29	1.8	1.8	3.0	2.0	**2.5**	3.3	3.8	3.0	3.3	**3.5**	**5.0**	B 1	Because the eart	D 4	Both arguments o	D 3	I don't know because
2006	30	4.3	4.5	4.2	4.7	**4.2**	4.7	4.7	4.4	4.3	**4.4**	**4.3**	B 2	Since the sun is t	B 4	Although we can a	D 5	Although I was tought
2006	31	3.5	3.5	4.0	3.3	**3.6**	3.8	3.8	3.6	4.0	**3.6**	**3.3**	B 2	The earth goes a	D 4	I do not know bec	D 3	I don't know because
2006	32	3.8	4.0	3.8	3.7	**3.7**	4.3	4.3	4.0	4.0	**4.1**	**3.3**	B 1	The sun remains	B 5	Acceleration only c	D 4	I do not know. This is
2006	33	4.8	4.5	4.8	4.7	**4.7**	4.8	4.7	5.0	4.3	**4.8**	**3.8**	B 1	The sun is not mo	D 2	In this course, we	D 4	Because I have not co
2006	34	4.3	3.5	3.4	3.0	**3.6**	3.8	3.0	3.0	2.3	**3.1**	**4.3**	B 3	Well, lets take ou	B 5	Everyday, we see	D 3	None of my observatio
2006	35	4.0	4.3	3.6	4.0	**4.0**	4.8	4.7	3.2	4.3	**4.1**	**2.5**	B 1	Seasons are crea	B 4	The earth goes arc	D 3	D is correct answer. N
2006	36	4.3	4.7	3.2	5.0	**4.2**	4.3	4.5	3.6	5.0	**4.2**	**3.3**	D 1	I am stuck betwe	D 4	I don't know beca	D 4	I don't know because

	MPEX											Teach	Earth-Sun				Black Hole	
				Pre					Post			Eval	Pre		Post			
Year	ID	R	I	Coh	Con	Avg	R	I	Coh	Con	Avg	Avg	#	text	#	text	#	text
2006	37	4.3	3.7	4.0	3.3	**4.0**	4.5	4.3	4.0	4.7	**4.1**	**4.8**	B 2	The earth goes ar	D 5	I do not know bec	D 4	I do not know because
2006	38	4.0	2.7	3.6	2.7	**3.2**	2.8	3.7	3.8	3.7	**3.2**	**3.3**	B 2	The sun's gravita	B 4	I think the relative	D 4	I do not know because
2006	39	5.0	3.2	3.6	3.7	**3.5**	5.0	3.0	3.4	3.0	**3.3**	**2.5**	B 1	The sun is a star	B 3	The earth goes aro	D 3	I don't know anything
2006	40	4.3	3.5	3.6	3.3	**3.6**	3.5	4.0	3.8	4.0	**3.9**	**3.3**	B 1	All the planets orl	D 4	I do not know whe	D 4	I do not know whther
2006	41	4.5	4.5	4.2	4.3	**4.3**	4.3	3.5	4.4	3.0	**3.9**	**4.1**	B 1	The Earth goes ar	D 4	*She wrote down	D 4	I simply know nothing
2006	42	4.5	4.8	3.6	4.7	**4.1**	4.0	4.7	3.4	4.7	**3.9**	**4.6**	B 1	Because all the ot	B 5	The earth goes aro	D 4	If I look in a really pov
2006	43	4.8	4.3	3.8	4.3	**4.2**	5.0	4.8	3.8	5.0	**4.6**	**2.9**	B 2	The sun is a mucl	B 3	Though through m	D 3	Black holes are somet
2006	44	3.8	3.7	3.0	4.0	**3.1**	4.0	4.2	3.2	3.5	**3.8**	**2.3**	B 1	The earth, along	B 2	WE know from our	D 3	I do not know precisel
2006	45	3.8	4.5	3.6	4.0	**3.9**	3.5	4.2	4.0	4.3	**3.9**	**2.3**	B 1	As the earth goes	D 4	I don not know wh	D 4	I don't know which sta
2007	46	4.3	4.0	3.8	4.3	**3.8**	4.0	3.8	3.8	4.0	**3.9**	**4.3**	B 1	Copernicus's helic	B 5	I think the helioce	D 4	I cannot accurately co
2007	47	4.3	3.3	3.4	3.0	**3.4**	4.8	4.0	3.4	3.0	**3.8**	**3.4**	B 1	The sun is a star	D 3	I don't know. This	D 5	There are rumors that
2007	48	3.8	4.2	3.6	4.7	**3.8**	4.5	4.2	3.6	4.3	**4.1**	**2.4**	B 1	If the sun went a	B 5	Some of the event	D 4	I chose answer D beca
2007	49	4.0	4.4	4.2	4.0	**3.9**	4.0	4.3	4.2	4.3	**4.1**	**4.5**	D 1	It's theoretical to	D 4	If there is a perso	D 3	I don't care whether b
2007	50	5.0	4.5	3.5	4.3	**4.3**	5.0	4.8	3.6	4.7	**4.5**	**4.0**	B 1	The earth is smal	D 5	So far we can acc	D 5	Taking the role of a sc
2007	51	4.3	4.3	4.4	4.3	**3.9**	3.5	4.7	4.2	4.7	**4.2**	**4.3**	B 1	The sun exerts a	D 2	As we have obser	D 5	I do not know that bla
2007	52	3.8	3.5	3.8	3.3	**3.6**	4.8	4.2	4.0	4.3	**4.0**	**1.9**	B 4	The sun has a lar	B 5	We can observer t	C 3	Neither A or B are cor
2007	53	4.5	4.2	3.6	4.3	**3.9**	5.0	5.0	4.2	5.0	**4.8**	**4.0**	B 1	It has been prove	A 4	We can perfectly a	D 4	I do not know about t
2007	54	4.3	3.7	3.8	3.0	**3.8**	4.0	3.8	3.6	4.0	**3.8**	**4.8**	B 1	The earth revolve	B 4	Let's look at answ	D 5	If black holes did exist
2007	55	4.0	4.2	4.0	4.0	**3.9**	3.3	4.0	3.4	4.0	**3.5**	**3.9**	B 4	The mass of the s	D 5	I believe the answ	D 5	The is answer is that I
2007	56	4.8	3.7	3.8	3.7	**3.8**	4.8	4.5	4.2	4.3	**4.4**	**3.4**	B 1	It's been proven t	D 5	I do not know, bec	D 4	I do not know because
2007	57	4.3	4.5	4.2	4.3	**4.2**	4.0	4.3	4.2	4.0	**4.2**	**4.0**	B 2	The sun is far lar	B 2	From our observat	D 4	It is quite possible tha
2007	58	4.0	4.0	3.6	4.0	**3.8**	4.0	3.7	3.8	3.3	**3.8**	**4.5**	B 1	The earth like all	2	You can account fo	D 4	The existence of black
2007	59	4.8	3.7	3.2	3.0	**3.6**	5.0	4.3	3.6	3.7	**4.0**	**4.4**	B 1	The sun is much	B 5	First, we observed	A 2	It is possible that ther
2007	60	3.5	4.0	3.2	4.0	**3.6**	4.0	4.0	3.0	4.0	**3.7**	**4.5**	B 1	The earth orvits t	D 5	The relative motio	D 3	I know nothing about
2008	61	4.5	3.2	3.2	2.7	**3.6**	4.5	3.5	3.0	3.7	**3.6**	**4.0**	B 1	The sun is known	B 4	Of the 4 following	D 4	The option I chose for
2008	62	4.0	3.2	2.6	2.7	**3.2**	5.0	3.5	4.2	3.3	**4.3**	**4.5**	B 1	The earth goes ar	B 3	The answer the ea	D 5	I do not know which is
2008	63	4.0	3.4	3.3	4.0	**3.7**	5.0	3.3	3.0	3.7	**4.1**	**4.5**	B 1	It takes 365.25 d	B 4	I feel that the eart	D 4	I do not know much a
2008	64	4.0	3.3	3.8	3.3	**3.9**	4.8	3.5	4.0	4.0	**4.2**	**4.3**	B 1	There are other p	D 5	I do not know if th	D 4	I do not know anythin
2008	65	5.0	3.7	3.0	3.0	**3.9**	5.0	3.3	2.6	3.0	**3.8**	**4.3**	B 2	The sun has grea	D 3	I've seen series of	D 5	I think that D is most
2008	66	2.8	3.2	3.6	4.3	**3.5**	3.3	2.0	3.0	2.3	**2.9**	**4.5**	B 1	Theearth goes ar	D 5	I can account for	D 3	I have absolutely no id
2008	67	3.5	3.0	3.0	3.3	**3.4**	4.3	3.7	3.4	3.7	**4.1**	**4.5**	B 2	By the laws of mo	D 5	Based solely on th	D 5	I can not say anything
2008	68	3.5	3.5	3.2	3.3	**3.5**	4.8	3.7	3.8	4.0	**4.2**	**3.8**	B 1	The sun is at the	B 3	In class all of our	C 1	A black hole can be de
2008	69	5.0	3.8	4.2	4.0	**4.4**	4.8	4.2	4.8	3.7	**4.4**	**3.3**	C 1	Bothe the earth a	C 4	We can account fo	A 2	I don't know enough a
2008	70	3.3	2.7	2.6	2.7	**2.9**	3.3	3.0	2.4	3.0	**3.0**	**2.0**	B 1	The Earth has an	D 5	Although it is com	D 5	Even though I have he
2008	71	4.3	3.3	3.0	3.0	**3.4**	5.0	3.5	3.8	3.3	**4.2**	**4.0**	B 1	Solar eclipses and	D 4	Only using the app	D 5	I can't support or disp
2008	72	4.3	3.7	3.2	3.3	**3.6**	4.0	3.7	4.0	3.7	**3.9**	**3.0**	B 1	All planets revolv	D 4	We don't actually	D 5	I do not know because

	MPEX											Teach	Earth-Sun					Black Hole		
				Pre					Post			Eval	Pre			Post				
Year	ID	R	I	Coh	Con	Avg	R	I	Coh	Con	Avg	Avg	#	text	#	text		#	text	
2008	76	5.0	3.3	3.4	3.3	**4.0**	5.0	3.3	3.8	3.0	**4.1**	**4.0**	B	2 This can be expla	D	5 From our (human)		D	3 I don't have an author	
2008	77	5.0	3.3	3.2	3.7	**3.8**	5.0	3.7	2.8	3.7	**3.8**	**3.0**	B	1 In the solar syste	B	5 I believe that the		D	4 I really have no clue w	
2008	78	4.5	3.2	4.0	2.7	**4.0**	4.5	3.2	3.6	2.7	**3.9**	**4.3**	B	1 The earth revolve	B	5 1) There are celes		D	3 Although we have hea	
2008	79	4.8	2.8	3.2	2.0	**3.5**	4.8	3.5	3.2	3.3	**3.9**	**4.5**	B	1 The sun has more	B	4 I believe the earth		D	5 Nowadays there are s	
2008	80	4.0	2.5	2.8	2.3	**3.2**	4.3	3.5	3.2	3.7	**3.7**	**3.0**	B	2 The sun has a ma	D	3 I do not know whe		D	3 Both statements could	

Appendix A.2 - Labs

Motion Detector Lab

Introduction:

In this lab you will use a motion detector, hooked up to a computer to gain experience in interpreting "position vs. time" and "velocity vs. time" graphs. The motion detector uses sound waves to find the distance of an object in front of it at different times. This information is fed into the laptop which uses the software provided to plot the information in real time.

Setup:

Make sure that both the computer and motion detector are switched on and that the software is running. Take a few minutes to familiarize yourself with the software. Here are some important points:

1. To change number of graphs, go to the View menu and select Graph Layout.
2. To change the type of graph, click on the y-axis label.
3. To change the range of either axis, click on the axis and type in the maximum and minimum value OR click on the last number at either end of the axis.

Part 1: Familiarization with the Detector

1. Set the program to display only one position--time graph.
2. Set the range of the Time axis to: 0 to 4 seconds.
3. Set the range of the Distance axis to: 0 to 2.5 meters

4. Have one person stand in front of the detector and have someone else push the Collect button in the progam. Start to walk back and forth in front of the motion detector when it starts to make noise.
5. Important: There is a minimum and maximum distance for which the detector will work. By moving back and forth, find the minimum and maximum distances.
6. Try collecting data a few times just to get some experience with this setup. Give everyone in the group a chance to try it out.

Part 2: Position-Time Graphs

1. For each question below:

- sketch a prediction of the position-time graph in the space provided
- produce the graph using the motion detector and sketch the result on the same graph in a different color.

Important: do not sketch the entire graph produced by the computer, just sketch the relevant part of the graph

a. Start at about ½ meter from the detector and walk away from the detector slowly and steadily.
b. Start at about ½ meter from the detector and walk away from the detector quickly and steadily.
c. Start at the 2 meters from the detector and walk towards the detector slowly and steadily.
d. Start at the 2 meters and walk towards the detector quickly and steadily.

2. Question: How does the graph made by walking towards the detector slowly compare with the graph made by walking towards the detector quickly?
3. Question: How do the graphs made by walking towards the detector compare with graphs walking away from the detector?
4. Predict the position-time graphs for the situation described below. Sketch your predictions in the space provided and compare your prediction with the rest of your group. Next, produce the position-time graph using the motion detector and sketch the result in a different color.
    a. Start at about ½ meter from the detector
    b. Walk away from detector quickly and steadily for 1 second
    c. Stop for 2 seconds
    d. Walk towards detector very slowly and steadily for 2 seconds
5. Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature
6. Write down in words the steps necessary to qualitatively produce the position-time graph shown on the right.
7. Try several times to re-produce the position-time graph shown above.
8. Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature
9. (207 labs only) For the graph on the right, use the slope to find the velocity:
    a. during the first 5 seconds
    b. during the last 5 seconds

Part 3: Velocity-Time Graphs

1. Change the graph to display only Velocity-time graphs with a velocity range from -2.0 m/s to 2.0 m/s.
2. Make velocity-time graphs for each of the types of motion described below. In each case, try producing the graph several times and sketch a reproduction of the graph in the space provided.
    a. Start at about ½ meter from the detector and walk away from the detector slowly and steadily.
    b. Start at about ½ meter from the detector and walk away from the detector quickly and steadily
    c. Start at 2 meters and walk towards the detector slowly and steadily.
    d. Start at the 2 meters and walk towards the detector quickly and steadily.
3. Question: What is the difference between graphs made by walking away slowly and walking away quickly?
4. Question: What is the difference between graphs made by walking steadily away from the detector and steadily towards the detector
5. Important: Show and explain the your answers to the last 4 Questions to the TA and get a signature before moving on: TA Signature
6. Predict the velocity-time graph produced by the following motion and sketch your prediction in the area provided below. Then perform the actions and sketch the result in a different color.
    a. Start at the 2.5 meters and walk towards the detector quickly and steadily for 1 second

b. Stop for 2 seconds

c. Walk away from the detector slowly and steadily for 2 seconds

7. Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on

Part 4: Position-Time and Velocity-Time Graphs

Now we will relate position-time graphs to their corresponding velocity-time graphs.

1. Change the program to display 2 graphs, one for position-time and one for velocity-time. Set the range on both axes to be the same as the graphs below.
2. Predict the velocity-time graph that corresponds to the position-graph below, sketch it in the velocity-time graph provided.
3. Now use the motion detector to reproduce the position-time graph above as closely as possible. Sketch the corresponding velocity-time graph using different color on the same graph as your prediction (do not erase your prediction).
4. Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature
5. Question: How would the position-time graph be different if you moved faster or slower?
6. Question: How would the velocity-time graph be different if you moved faster or slower?

Part 5: Acceleration

1. Use the motion detector to reproduce the curved line position-time graphs below as best as you can.
2. Describe how you moved to produce the 2 graphs.
3. Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature
4. (207 labs only) For the first graph, estimate the velocity at the following times: (HINT: use the slope of the tangent)
    a. t=0
    b. t=3
5. (207 labs only) For the first graph, estimate the average acceleration between t=0 and t=3 seconds.

Part 6: Qualitative questions

1. How can you tell from a velocity-time graph that the object has changed direction?
2. How can you tell from a position-time graph that the object has changed direction
3. How can you tell from a velocity-time graph that your velocity is constant?
4. How can you tell from a position-time graph that your velocity is constant?

Part 7: Final question

1. Get a fan-propelled cart from the TA and set up the motion detector to collect data for the cart's motion as it movies toward the detector as show in the diagram below.
2. Produce a Position vs Time and Velocity vs. Time graphs for motion of the cart accelerating towards the detector and sketch them in the space provide below.
3. Important: Show and explain the graph produced in the last Question to the TA and get their signature before moving on: TA Signature
4. (207 labs only) From the graph on the computer calculate the acceleration of the cart. Explain how you found the acceleration and show your work.

Simple Harmonic Oscillator Lab

Introduction

In this lab you will study the simple harmonic motion of a mass hanging from a spring using the motion detector.

Motion Detector Reminders:

1. To change number of graphs, go to the View – Graph Layout menu
2. To change type of graph click on y-axis label.
3. To change graph range click on number at either end of x or y axis.
4. Click "Collect" to collect data.
5. Explore the program on your own to learn more

Figure 1 depicts the experimental setup. The mass which is attached to the spring is free to oscillate up and down. The motion detector feeds information on the mass' motion into the laptop where plots of the mass's position and velocity are made in real time.

Part A: Predictions

Before getting a spring to perform the experiments you must make the following predictions. Assume the mass and spring are hooked up as shown above and the mass is pulled down and released, setting it into motion at t = 0. In Figure 2 sketch your prediction for the position vs. time (d vs. t), velocity vs. time (v vs. t) and acceleration vs. time (a vs. t) graphs for oscillation over 1 period.

Part B: Equilibrium

Hang a 1.000 kg mass from the spring such that the mass is not moving. The spring will stretch by an amount $x_{\circ}$ (as shown in Fig 3). The force of the spring depends on the spring constant k and the length $x_{\circ}$, it is given by:

$F_{spring} = -k\, x_o$

1. Assuming the mass is at rest at the bottom, draw the forces on the Free Body Diagram provided. Label each of the forces.
2. Calculate the spring constant 'k'. Show how you arrived at your answer.

We will call the position of the mass when it remains at rest is the equilibrium position. Note that the net force on the mass at equilibrium position is 0.

Part C: Observations of Simple Harmonic Motion

First, hang 1.000 kg from the spring. Set Logger Pro to plot position vs. time, velocity vs. time, and acceleration vs. time. Collect a set of data with the mass at rest. Write down the equilibrium position of the mass. Pull the mass down a few centimeters from the equilibrium position and release it to start motion. Collect a set of data while the mass is moving.

Calculations:

1. Describe how the mass moves relative to the equilibrium position.
2. Calculate the max velocity from the position vs. time graph. Show your calculations. It should agree with the value from the velocity time graph.
3. At what position is the velocity a maximum?

4. Calculate the min velocity from the position vs. time graph. Show your calculations. It should agree with the value from the velocity time graph.
5. At what position is the velocity a minimum?
6. Calculate the maximum acceleration from the velocity vs. time graph. Show your calculations. It should agree with the value from the acceleration vs. time graph.
7. At what position is the acceleration a maximum?
8. Calculate the minimum acceleration from the velocity vs. time graph. Show your calculations. It should agree with the value from the acceleration vs. time graph
9. At what position is the acceleration a minimum?
10. Compare your position, velocity and acceleration graphs with your predictions on page 1. Resolve any discrepancies.

Part D: Investigation of the Period of Oscillation

1. Predictions:
    a. Predict how the period of oscillation will change when the mass is changed. Explain your prediction.
    b. Predict how the period of oscillation will change with different initial amplitudes. Explain your prediction.
2. Experiment: Devise experiments to see how the Period depends on Mass and Amplitude. Your results must include the following graphs:
    a. Mass vs. Period
    b. Mass vs. Period^2
    c. Amplitude vs. Period

d. Amplitude vs. Period^2

3. Compare your experimental result with your prediction. Resolve any discrepancies.

Part E: Two-spring experiment

1. Prediction: Predict how the period of oscillation will change when the mass is hung from 2 springs which are attached in series. Explain your prediction.
2. Experiment: Devise and implement an experiment to test how adding a second spring changes the period. Explain the details of your experiment.
3. Compare your experimental result with your prediction. Resolve any discrepancies.

Part F: Energy conservation

Collect a set of position vs. time, velocity vs. time and acceleration vs. time data for an oscillating mass of 1.000 kg.

1. Calculation: Test conservation of energy by calculating and comparing the total energy of the system at 2 point along the mass's path. Take the first point at to be at the highest position of the mass and the second point when the mass is at the equilibrium position.

As a mass oscillates its amplitude will very slowly decrease over time.

2. Experiment: Devise an experiment to determine how long it takes for the amplitude to be reduced to 2/3 of the original amplitude? Explain how you found this answer.
3. Does the period change as the system loses energy? How did you determine your answer
4. The reduction in amplitude represents a loss of energy by the system. Where does the energy go?

Appendix A.3 – Twin Paradox Problem

The Twin Paradox Questions Posed to the Brothers

The brothers were presented with this question and given a pen, some paper and a modern physics textbook. There were asked to discuss their ideas out loud as they answered the question with minimal interference from the interviewer.

1. Consider twins Aaron and Bonnie both at location Earth. On the day of their 30th birthday, Aaron is at rest on Earth while Bonnie is on a rocket ship just above Aaron moving 0.6c. Their clocks read the same time at this instant. Bonnie travels directly to Planet X which Aaron measures to be 6 light years from Earth. (See figure 1.)
A. According to Aaron:
-How much time passes on his own clock for Bonnie to reach Planet X?
-How much time passes on Bonnie's clock for her to reach Planet X?
B. According to Bonnie:
-How much time passes on her own clock for her to reach Planet X?
-How much time passes on Aaron's clock for her to reach Planet X?
C. According to Aaron, when Bonnie reaches Planet X:
-What time is on his own clock?
-What time is on Bonnie's clock?
D. According to Bonnie, when she reaches Planet X:
-What time is on her own clock?
-What time is on Aaron's clock?

2. When Bonnie reaches Planet X, she quickly comes to a stop and returns to Earth with the same speed.
A. According to Aaron:
-How much time passes on his own clock during Bonnie's return trip to Earth?
-How much time passes on Bonnie's clock during her return trip to Earth?
B. According to Bonnie:
-How much time passes on her own clock during her return trip to Earth?
-How much time passes on Aaron's clock during her return trip to Earth?

3. Once reaching Earth, Bonnie comes to a quick stop and reunites with her brother.
A. According to Aaron:
-How much total time has passed on his own clock since the beginning?
-How much total time has passed on Bonnie's clock since the beginning?
B. According to Bonnie:
-How much total time has passed on her own clock since the beginning?
-How much total time has passed on Aaron's clock since the beginning?
C. After the reunion, Aaron and Bonnie's physics teacher joins them and gives a poster of Einstein to the twin who has aged less. Who gets the poster?

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