A DESCRIPTIVE STUDY OF COOPERATIVE PROBLEM SOLVING INTRODUCTORY PHYSICS LABS

A DISSERTATION

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Dedication

To Mary Knutson, my wife, for her love and support. Also to Siri and Dan Drontle and to Maja and Cara Knutson – keep strong those sparks of curiosity, adventure, and learning.

Abstract

A Descriptive Study of Cooperative Problem Solving

Introductory Physics Labs

The purpose of this study was to determine the ways in which cooperative problem solving in physics instructional laboratories influenced the students' ability to provide qualitative responses to problems. The literature shows that problem solving involves both qualitative and quantitative skills. Qualitative skills are important because those skills are the foundation for the quantitative aspects of problem solving. (Chi, et al., 1981). The literature also indicates that cooperative problem solving should enhance the students' performance. As a practical matter surveys of departments that require introductory physics classes expect their students to have general qualitative problem solving skills.

The students in this study were asked to solve problem(s) before coming to a lab session and then cooperatively assess whether or not their answers were correct by conducting a laboratory activity for which they had to plan the procedure and obtain the necessary results. TA's were expected to provide instruction under a cognitive apprenticeship model.

The results showed that the cooperative problem solving laboratories had almost no impact on the students' problem solving skills as measured from the start of a two hour

lab session to the end of the lab session...The reason for this may have been that students did not have enough experience in the solving of different kinds of problems in the two domains of Newton's second Law and gravitation to overcome their misconceptions and become competent. Another possibility was that the TA's did not follow the cognitive apprenticeship model as consistently as might have been needed.

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Chapter 1 Introduction

Introduction and Rationale

A discussion about laboratories in introductory physics raises many questions about what takes place in them. The importance of physics labs, and the role they play in helping students gain insight and understanding, is a matter of concern for physics departments and, of course, physics instructors. The concern does not stop at the exit of the physics building. Physics classes are required by many departments, from engineering departments, to natural resources and biology. What is taught in physics classes and how it is taught has an impact on students from many areas of study. Problem solving is high on the list of important skills that departments outside of physics would like to have emphasized in the physics courses taken by their students. One of the main goals of these courses, *as requested by the departments requiring the courses*, is to improve students' physics problem solving skills (Foster and Heller 1997). According to Heller, Keith, Anderson and Foster, most students enter the introductory physics courses with "poor" problem-solving skills (Heller et al. 1992) (Foster 2000). Since problem solving skills are considered important in physics classes, we can see that putting emphasis on developing these skills should be considered a high priority.

We can ask how physics labs are related to the overall study of physics. Physics is ultimately about trying to describe and understand the physical world. Related to this, we have a comment by Arnold Arons, one of the early leaders in physics education research "...most physicists have a deeply rooted, intuitive feeling that laboratory experience is essential to learning and understanding our subject..." (Arons 1997). A large amount of time, effort, and money is expended on introductory physics labs. Questions about of the efficacy of physics labs are often raised or are not far from the surface when discussions focus on introductory physics classes (Redish 2003). Toothacker also raises some of these questions. (Toothacker 1983)

This descriptive study provides information about the effects of the labs at the University of Minnesota and focuses on a particular component of a key part of the labs. This key part is problem solving and the particular component of interest deals with the qualitative skills of problem solving. These labs are referred to as Cooperative Problem Solving (CPS) labs. The approach used in these labs is unique because it is an integration of working in groups to do cooperative problem solving of "context rich" problems. Context-rich problems are designed to have many characteristics of authentic or real life problems. (Heller and Hollabough 1992) (More about context-rich problems in chapter 2). The approach also involves decision making with respect to choosing the types of measurements needed to check the results of the problem solving. This use of the lab to check the adequacy of problem solutions is unique. Problem solving in other schools is often only considered part of the lectures and discussion sessions.

The number of references to problem solving in physics classes is very large. Two examples are given below. One is an article by Leonard et al. and the other is a Resource Letter on problem solving, in the American Journal of Physics, which includes many additional references. Even the Resource Letter covers only a portion of the literature on problem solving.

“Two primary goals in teaching introductory physics are to help students learn major concepts and principles, and to help students learn how to apply them to solve problems.” (Leonard et al. 1996, 1495) As pointed out in a 2004 American Journal of Physics Resource Letter: “Problem solving is an integral part of most physics courses.” (Hsu et al. 2004) The role of labs in this ‘integral part’ of physics courses is certainly worthy of investigation.

This research project is one in a long series of research and development studies, started some 20 years ago, investigating Cooperative Problem Solving (CPS) in introductory physics courses at the University of Minnesota. The Physics Education Research group at the University of Minnesota has investigated the effect of modeling a logical, organized, problem solving framework during lecture, and coaching students explicitly with this framework during Cooperative Problem Solving (CPS) recitations (sometimes called discussion sessions). These recitations are a required part of the course. They meet one hour per week with the same teaching assistant (TA) and the same students who are in the lab section.

Previous studies have addressed problem solving in the lectures and the recitations (discussion sessions). This study will look at Cooperative Problem Solving in the labs.

Several topics concerning problem solving have been addressed by the University of Minnesota Physics Education Research (PER) group in the following publications and theses.

- Problem solving performance (Heller et al., 1992) (Blue 1994) (Foster 2000)
- Hierarchical organization of physics knowledge (Keith 1993)
- Interaction patterns while co-constructing a problem solution in CPS recitations (Hollabough 1995)
- Conceptual understanding of force and motion (Blue 1997)
- The effect of introducing computers into an introductory physics problem-solving laboratory (McCullough 2000)
- Faculty conceptions about the teaching and learning of problem solving in introductory calculus-based physics (Henderson 2002)
- An explanatory model of physics faculty conceptions about the problem-solving process (Kuo 2004)
- Rubric for analyzing student problem solving skills (Docktor 2009)

This study is a natural next step in the series of studies conducted by the Physics Education Research group. There have been no studies to determine whether the CPS labs contribute to improving students' qualitative analysis skills within the limited context of the specific lab problems. In fact, there have been very few studies that relate the effectiveness of a lab to specific course goals, such as improving students' physics problems solving skills. (Redish 2003, 162).

Research Question

This research involving the description of cooperative problem solving (CPS) introductory physics labs will focus on students' qualitative analysis skill levels in problem solving. We are interested in students' qualitative analysis skill levels in problem solving and their change in skill levels, over time. The research question is as follows:

> **In what ways, if at all, do students' qualitative analysis skill levels change, in the domain of Newton's 2nd law and in the domain of gravitational force, from pre-test to post-test during a two hour lab period, and as measured during three successive lab periods each of the lab periods being one week apart? For the purposes of this study the qualitative analysis of a lab problem includes the physics and mathematical representation of a problem.**

General Information about Cooperative Problem Solving (CPS) Labs at the University of Minnesota

Since a primary purpose of these labs is to develop problem solving skills, it is important to provide a structure that provides students an opportunity to practice these skills. As part of that structure, the lab work starts before the actual lab session begins. Students are expected to solve, or at least try to solve, the assigned lab problem(s) **before** the lab session. The students are expected to answer warm-up questions (or method questions) on the lab and hand them in the day before the lab session. The warm-up questions are designed to provide guidance in solving the lab problems.

During the lab session, students use physical equipment and computer interfaces to check whether they solved a problem correctly. Typically, it takes students about 1 hour to check their solution for one lab problem. They analyze the data and reach a conclusion in class before starting to check their solution for the next assigned problem. This is one way that problem-solving labs differ from inquiry or verification labs. The experiment and data collection are not the foci of the lab – they are just a way to check a problem solution. If checking the problem solution with the lab equipment does not provide agreement with the proposed solution, the students have an opportunity to revisit their first solution, as a small lab group, and investigate the source of their difficulty. The TA should be available for coaching if the group is not having success on its own. This working with members of a group, with access to and help from the TA, is a part of a cognitive apprenticeship model as outlined by Farnham Diggory in "Paradigms of Knowledge and Instruction." (Farnham-Diggory 1994)

The problem-solving labs are designed to provide students with three types of coaching in physics problem solving skills: (1) Method Questions (or Warm-up Questions) presented in the lab manual, (2) Peer coaching while the students are working in their groups, and (3) TA coaching of the small cooperative groups. (See 0 Appendix for a sample lab problem and a set of Method Questions).

Overview of This Dissertation

The following provides a brief guide to the remaining chapters in this dissertation.

Chapter 2 Literature Review

This chapter provides a review of the research relevant to this study.

Chapter 3 Research Methods

This chapter presents a description of the methods for the teaching of the labs, and the methods used for collecting and analyzing data.

Chapter 4 Results

This chapter presents the results.

Chapter 5 Conclusions and Implications

This chapter provides a brief summary of the study and suggests possible directions for future studies.

Bibliography

Appendix

Chapter 2 Literature Review

Rationale for Doing this Study

General Perspectives on Physics Labs

What is the role of laboratory work in introductory physics classes? The type of laboratory varies from school to school. Different types include "cookbook" labs in which "…students will go through a prescribed series of steps to demonstrate the truth of something taught in lecture or read in the book." (Redish 2003, 118). Another type of lab is called *guided discovery*. In this approach, "…students are guided to observe phenomena and build for themselves the fundamental ideas via observation." (Redish 2003, 118) Another example of lab materials is called RealTime Physics (RTP). It is a series of laboratory materials designed by Sokoloff, Thornton, and Laws "…that can be used in a traditional lecture/lab/recitation teaching environment." (Redish 2003, 164). Sokoloff et al. use "…cognitive conflict, bridging, and the learning cycle (exploration/ concept introduction/ concept application…)." (Redish 2003, 165). Also used by Sokoloff et al. is a combination of the above pedagogical methods with "…computer-assisted data acquisition to help students re-map their interpretation of their experience with the physical world." (Redish 2003, 165).

"A specific type of active-engagement classroom is the *workshop* or *studio class*. In this environment, the lecture, laboratory, and recitation are combined in a single classroom. In workshop classes, most of the class time is taken up by periods when the students are actively engaged in exploring the physics using some laboratory equipment,…" (Redish 2003, 120). Priscilla Laws and others at Dickinson College have developed a classroom layout for Workshop Physics that includes tables around the perimeter with computers for every two people. There is group interaction space in the center that can be used for demonstrations. (Redish 2003, 120). "[W]orkshop-style classes have been developed at RPI [Rensselaer Polytechnic Institute] for Studio Physics and at North Carolina State for the SCALE-UP project." (Redish 2003, 121) The SCALE-UP project is meant to be a highly collaborative, hands on, computer rich, interactive learning environment for large enrollment classes. (See the web page: www.ncsu.edu/per/scaleup.html)

The introductory physics labs at the University of Minnesota are different in that they emphasize problem solving, in step with the problem solving of the other parts of the course (discussion sections, lectures, problem assignments and problems on quizzes and the final exam). The approach is consistent with the idea expressed in a Resource Letter: "Problem solving is an integral part of most physics courses. Many instructors would like their students to learn to use physics principles and concepts to solve problems…" (Hsu et al. 2004). The research in this current study takes special note of the emphasis on the verification of problem solutions using laboratory activities.

There are qualitative and quantitative aspects to problem solving in physics. This research focuses on the qualitative aspects of problem solving related to the lab work. As mentioned elsewhere in this dissertation, these labs at the University of Minnesota are rather unique. Studying them, and in particular investigating possible changes in student skill levels in the qualitative aspects of problem solving, addresses an area of research that is of interest to physics departments and physics instructors. Unfortunately, there is a lack of actual research in this area. As Redish says: "Much more research will need to be done in order to figure out what learning goals can be effectively accomplished in the laboratory environment and how." (Redish 2003, 163). What are students actually learning in physics labs? Research on this topic is lacking. (Kenneth Heller, pers. comm.)

There are, of course, different perspectives on the importance and usefulness of labs. Redish suggests: "The laboratory is the traditional instructional environment that is, in principle, best set up for independent active-engagement learning in line with our cognitive model of learning." (Redish 2003, 163) 'Physics laboratories are essential' is not the only point of view to be found in the history of physics education. According to

Arnold Arons: “The usefulness and effectiveness of the introductory laboratory have been bones of contention in physics teaching as far as one cares to go back in the literature.” (Arons 1997). An example of a critical point of view of physics laboratories is provided by Toothacker in, A Critical Look at Introductory Laboratory Instruction. (Toothacker 1983) This point of view is also pointed out in a paper by Fred Reif and Mark St. John as they suggest sobering answers to the question of what students actually learn in the laboratory part of an introductory college-level physics course. They found “…that most students cannot meaningfully summarize the important aspects of an experiment they have just completed. Usually they recall some of their manipulations in the laboratory, but are unable to articulate the central goal of the experiment, its underlying theory, or its basic methods.” (Reif 1979) These sentiments are reinforced by evidence provided by Edward (Joe) Redish (Redish 2003, p. 162) from observation of traditional laboratories. He tells us: “Our video tapes show students spending most of the period trying to read the manual and figure out what it wants them to do. The students make little or no attempt to synthesize in order to get an overview of what the point of the lab is. Almost all of the discussion concentrates on the concrete questions of how to configure, run, and get information from the apparatus. There is little or no discussion of the purpose of the measurement, how it will be used, the physics to be extracted, or the limits of the measurements.” (Redish 2003, 163)

As implied above, there should be better ways of doing labs. At the University of Minnesota, the labs are designed to have students attempt to solve the lab problems, with the help of warm-up questions, at least a day in advance of the lab session. Students can work individually or in groups of their own choosing before the lab session. In the lab session, students work in cooperative groups to compare their methods and solutions or, if they have been unable to complete the solutions, they can work in their cooperative groups to solve the problem(s). They also use lab equipment, including computers, to verify their results. This approach is based on cooperative problem solving (CPS). This design uses a cognitive apprenticeship model in the labs and throughout the course. (Brown et al. 1989) and (Farnham-Diggory 1994).

Design of Cooperative Problem Solving (CPS) Labs at the University of Minnesota

The lab manual tells students: "This lab manual is designed, in part, to help you recognized where your ideas agree with those accepted by physicists and where they do not. It is also designed to help you become a better physics problem solver." (Heller and Heller 2005, 1) These cooperative problem solving labs (CPS) are in agreement with the general ideas of a 'speculative hopeful' nature expressed by Redish, that are previously mentioned. (Redish 2003). In the University of Minnesota introductory labs, the students work in cooperative groups of three to co-construct a solution to a context-rich physics problem. (More about these context-rich problems later.)

The cooperative learning literature supports the idea of using the CPS labs. Cooperative learning has five components, given below, which can be very important for successful cooperative work.

- Positive interdependence "sink or swim together"
- Individual and group accountability

- Promotive interaction, preferably face to face to promote each other's success
- Interpersonal and small group skills
- Group processing: Members discuss how well they meet goals and maintain effective working relationships (Johnson, et al., 1998)

The above components are important for effective functioning of the small lab groups of three students as they work on problem solutions and the verification of those solutions.

The cooperative problem solving, with students working in cooperative groups of three, is addressed in two papers directly related to physics labs at the University of Minnesota – (Heller et al. 1992) and (Heller and Hollabaugh 1992). Cooperative learning ideas developed from discussions with Johnson, Johnson, and Smith, were instrumental in the group work described in these papers. The ideas contributed by Johnson, Johnson, and Smith are developed in a book written by them. (Johnson et al. 1991). Further development of the ideas involved in cooperative groups are presented in another book by Johnson, Johnson, and Smith, published in 1998. (Johnson et al. 1998)

As mentioned earlier, the labs use a cognitive apprenticeship model. The books mentioned above by Johnson, Johnson and Smith provide a basis for the ideas used to design the cooperative problem solving aspect of the lab system, as well as the functioning system for the discussion (recitation) problem solving sessions.

The ideas and techniques for the functioning of the labs, developed by K. Heller, P. Heller, R. Keith, S. Anderson, and M. Hollabaugh through discussions with D. Johnson, R. Johnson and K. Smith, included the following:

- Optimum size for lab cooperative problem solving groups is three students.
- The make-up of the students in a group is determined by the TA.
- The TA changes the make-up of the particular students in a group three or four times each semester. This is intended to help students realize that it is not just their initial group that happened to function well, but that it is possible to have a well functioning group with a variety of different people.
- A group usually operates most effectively if the students are not academically homogeneous. For example three very successful students might proceed on the wrong track and then continue to the next problem, without realizing that a major mistake might have been made in the first problem. A less successful student might ask for clarification, and in so doing, cause the other students to catch the error that had been made. Usually, a spectrum of student academic success can provide overall group success.
- Groups composed of two females and one male, or three females, or three males should, on average, perform most effectively. Groups composed of two males and one female do not, on average, function as well as the combinations already mentioned.
- It is helpful to have the TA assign roles for the group participants. Useful roles are: 1) A manager, who makes certain the group works on what is to be accomplished and encourages the members of the group;

- 2) A recorder, who makes certain the necessary data is obtained and checks to see if everyone in the group has the necessary data;
- 3) A skeptic, who raises questions so students don't go off in the wrong direction without realizing it.

The apprenticeship format has been used for centuries in areas of work from pottery making, to auto mechanics, to medicine. "Cognitive apprenticeship methods try to inculturate students into authentic practices through activity and social interaction in a way similar to that evident – and evidently successful – in craft apprenticeship." (Brown et al. 1989) The physics labs are a very important part of this cognitive apprenticeship model. The model includes a lecture, where concepts are explained. Problem solving in a "modeling" format, when performed by the instructor, is meant to provide students with a sense of how concepts and principles can be used to understand ideas and to solve physics problems.

The discussion sessions provide an opportunity for students to work together in groups of three or four when solving a context-rich problem that would probably be quite difficult for one student to solve during the allotted time. (Context-rich problems are briefly mentioned in chapter 1 and later in chapter 2.) In an earlier study by Heller, Keith, and Anderson: "Group problem solutions were significantly better than those produced by the best problem solvers from each group on matched individual problems, particularly with respect to the qualitative analysis of the problems." (Heller et al. 1992) A TA is in charge of the discussion sessions, and provides guidance and help as the students work in groups on the problem(s).

In the labs, the students work in the same groups as they are in during the discussion sessions. The TA (the same TA as in the discussion session), who is the instructor for the lab, is available to help the groups by listening to their reasoning, asking questions – the answers to which can be helpful in guiding their work, and to generally providing coaching in solving the lab problems. The TAs help when help is needed, but also fade away so the group can have success working independently. The students are expected to complete the solution to the assigned problem and make a prediction based on their solution. They are expected to test their solution with lab equipment and the use of computers. Before testing solutions, they are expected to test their equipment to find the limits and optimum ranges for which they can obtain reliable data. In short, students are to experiment with the equipment so they can use it in an optimum manner and then devise a plan for checking their solutions. (Heller and Heller 2005)

Another aspect of the labs is the nature of the problems the students are asked to solve. As mentioned earlier, they are called "context-rich" problems and are designed to have many characteristics of authentic or real problems. "Context-rich problems are short stories that include a reason (if sometimes far-fetched or humorous) for calculating specific quantities about real objects or events." (Heller and Hollabough 1992) These context rich problems form the backbone of the work done by the students in the labs.

Obtaining Information about students' qualitative problem solving skills

To help describe the effects of the labs, we investigated components of students' success in solving the lab problems. In particular, we investigated the qualitative aspects of their problem solving. Pre and post questions were used to gather information about students' problem solving skills. An important part of the pre-post questions involved asking students to describe, in writing, certain forces that were part of the problem situation. Support for questions involving writing of this nature is given by Reif, Heller, and Woods. (Woods 1987)(Reif and Heller 1982).

Donald Woods tells us that knowledge is important for solving problems and when considering concepts, the "knowledge should be in a functionally useful form." (Woods 1987) This functionally useful form includes: "…the meaning of the concept and how to represent it in different symbolic forms: informal description; formal summary; etc..." (Reif and Heller 1982) A 'written description' comes under these categories, as given by the authors. Students are asked to write descriptions of forces involved in the context-rich problems. Questions asking for written descriptions in these pre-post questions are part of the attempt to investigate student learning related to qualitative problem solving. There is concern about students' skills in the qualitative aspects of problem solving because the qualitative aspects make up an essential component of problem solving. (Larkin 1979) Students' skills in these qualitative aspects may be assumed, and therefore not properly addressed in a physics course.

Some of the qualitative aspects of problem solving are commonly not discussed when the solution to a physics problem is presented. This is often true even when an instructor solves a problem in class. (Foster 2000, 42) Some qualitative aspects may be internalized by an instructor, and perhaps not verbalized. For example, forces may be described by an instructor using equations, while knowledge and understanding of the forces as would be expressed in verbal or written form is assumed by the instructor.

Leonard, Dufresne, and Mestre state: "When modeling problem solving for students, although we are usually careful to state verbally the principle or concept being applied to solve a problem, we often only *write down* the equations by which the principle is instantiated. Students, therefore, observe that it is the manipulation of equations that leads to solutions; their perception is that principles are abstractions that bear little relevance to obtaining answers to problems." (Leonard et al. 1996, 1496) When students write solutions to problems, they will also not generally express some of the qualitative aspects in writing. This can be problematic because understanding basic qualitative aspects is essential for a good understanding of the physics concepts that students are applying. (Leonard et al. 1996)

Learning and understanding related to physics labs

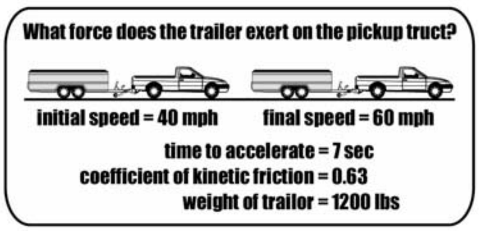
Research on the nature of problem solving: Qualitative and quantitative nature of problem solving

The extensive research on how experts (physics professors) and novices (beginning students) solve novel problems has explicated what expert and poor problem solving means. Experts solve novel problems by making increasingly abstract mental translations from the problem situation to an answer. If necessary, they first translate from the written or verbal description of the problem to an image (drawing) of the situation, including important information given in the problem (see Step 1 of Figure 2-1). Experts then translate from the image of the situation to a *physics representation* of the situation. This includes deciding which physics principle(s) can be used to solve the problem (e.g., kinematics, Newton's laws of motion, conservation of energy), drawing physics diagrams of the situation using these principles, defining symbols of physics quantities that describe a situation, and identifying symbolically the principles and constraints useful in describing the situation. This research in problems solving was the basis for the problem solving strategy that is taught in the University of Minnesota Program. (See Figure 2-1). (Heller and Heller 1995)

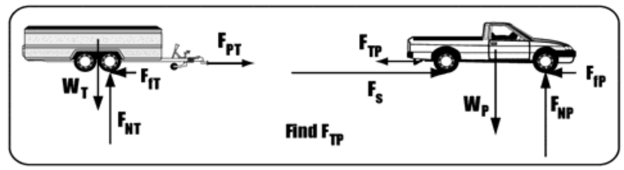
Figure 2-1 Qualitative Analysis of a Physics Problem

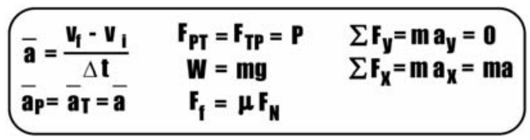
(Diagrams by Heller, P. M.)

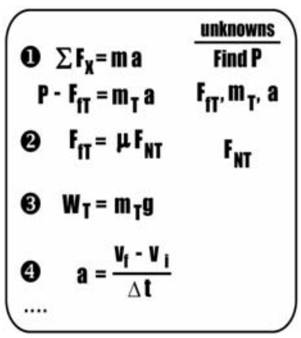
Step 1. Translating the Problem Description to a Visualization of the Problem



Step 2. Translating the Visualization to a Physics Representation of the Problem





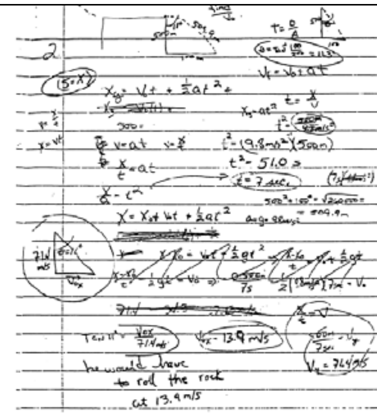


Step 3. Translating the Physics Representation into a Mathematical Representation.

Finally, experts translate from their physics representation to a mathematical representation of the problem. They use the defined symbols to write specific equations for the situation. Then, they try to determine if they have enough information to solve the problem (e.g., as many equations as unknowns). If there is not enough information, they return to the previous translations to identify any missing information. If no information was missed, but the problem is still not solved, they may try a different approach (e.g., energy instead of forces) (see Step 3 of Figure 2-1).

These three translations are often called the *qualitative analysis of the problem*. Experts do not begin mathematical manipulation of equations (algebra or calculus) until they think they are on the right track to solving the problem. (Larkin 1979) (Maloney 1994) (Henderson 2002) (Heller and Heller 1995).

Novices, on the other hand, often use a plug-and-chug approach. They start solving a problem by plugging numbers into formulas and chugging through the mathematics. Some novice students may use a pattern matching approach. They try to memorize patterns of mathematical solution for different kinds of problems, such as free-fall, projectile, inclined plane, or circular motion problems. (Chi et al. 1981) Novices often do not qualitatively analyze a problem based on fundamental concepts and principles of physics.



Typical Novice Problem Solution

Student thinking and the relation to the use of language in physics

A critical aspect of problem solving in physics is the students' understanding of the meanings of the physics terms they have to use – not the everyday meanings, but the proper physics meanings. Students encounter a variety of words and concepts in introductory physics. The words and concepts of core physics ideas are encountered in lectures, discussion sections, and labs. Words that have a special meaning in physics usually have a different meaning in everyday life, outside of physics. (Touger 1991) The vocabulary of physics can have significant implications for students. Ortiz, Rebello, and Zollman talk about this. They refer to the Sapir-Whorf hypothesis that tells us: "[W]e see and hear and otherwise experience very largely as we do because the language habits of our community predispose certain choices of interpretation." (Ortiz et al. 2003)

The use of language in physics plays a role in conceptual content. Leonard Talmy talks about the conceptual approach to language that: "is concerned with the patterns in which and the processes by which conceptual content is organized in language." (Talmy 2000, 2) Cognitive linguistics has "…addressed the structuring within language of such basic conceptual categories as those of space and time, scenes and events, entities and processes, motion and location, and force and causation." (Talmy 2000, 3)

Concepts, understanding them and their use in physics, plays a large role in understanding and working in the field of physics. The ideas expressed by the authors mentioned here indicate something about the importance of language in studying and understanding physics. We expect that language used in student descriptions of forces will provide some insight into the students' understanding of some physics concepts.[1] The student descriptions of gravitational force were examined and characterized to gain insight into their understanding of gravitational force. Students' understanding of the concepts determines how they represent a problem, and therefore is critical to all qualitative aspects of the problem they solve. This study looked in particular at students'

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[1] Talmy uses the term cognitive semantics in describing his research. He tells us that the word "semantics" indicates "the particular approach, the conceptual," within which his research is based. Talmy tells us that "semantics simply pertains to conceptual content as it is organized in language. Hence, the word "semantic" simply refers to the specifically linguistic form of the more generic notion "conceptual"." (Talmy, v1, p4;2000) It should also be noted that Talmy points out that "conceptual content is understood to encompass not just ideational content but any experiential content, including affect and perception." (Talmy, v1, p4; 2000)

understanding of gravitational force. (See the following section and the Rubric for Gravitational Force in Chapter 3, Table 3-1)

***What* do students think, with respect to forces in general and gravitational force in particular?**

The ideas presented here provided insight for developing the categories used in ranking students' understanding of gravitational force.

Four fundamental interactions of physics are acknowledged by physicists. They are gravitational force, electromagnetic force, the strong force, and the weak force (O'Connell 1998). Students might not hold this idea of forces as interactions. Maloney discusses this stating: "What is conspicuously missing from students reasoning about forces is any concept of the ultimate nature of forces as interactions." (Maloney 1990) Maloney cites the work of Terry and Jones who comment about students:

> "This suggests that they do not have an understanding of the concept of force and interactions between two objects or that the forces involved in the interaction can be described by the third law. There was no indication that pupils generally think of an interaction in terms of an equal and opposite pair of forces. Yet such an understanding is central to an understanding of the overall concept of force." (Terry and Jones 1986)

Tougher is in agreement with this discussion. He tells us: "The physicist thinks of forces as actions – more specifically as interactions." (Tougher 1991, 46)

Students hold a variety of other ideas. For some students, the force of gravity is considered “an entity which can be possessed, transferred, and dissipated (rather than an interaction)” (Chi 2008, 71) When asked to describe forces, some students will use the term “weight” to describe gravitational force. This could indicate the student means the term “weight” indicates the force of gravity is acting and the student assumes the reader will know that an interaction between the earth and an object is what is taking place. On the other hand, the use of “weight” could suggest weight is a property of an object, (such as a car or a block of wood). Chi tells us some students might consider that “weight is an intrinsic property of an object (even though gravity is conceptualized [by the student] as an external factor that pulls harder on heavier objects.).” (Chi 2008, 71)

Students sometimes consider gravity a separate entity, outside of an object that is being pulled by the earth. According to Reiner, Slotta, Chi, and Resnick, “Novices have a definite conception of weight in their substance schema that has nothing to do with the gravitational field as defined by physics.” (Reiner et al. 2000, 13)

Brookes and Etkina suggest a hypothesis that “students are failing to coordinate appropriately the many different descriptions that they learn from physicists’ language.” (Brookes and Etkina 2007)[2] For example, the phrase ‘force of gravity’ is used by physicists to mean the interaction between two objects that results in an attraction which is directly proportional to the quantity of mass of each object and is inversely proportional to the square of the distance between the centers of the objects. The use of

[2] Brookes and Etkina provide an example from quantum mechanics concerning the potential energy graph in terms of physical objects (well, barrier, etc.).

the phrase 'force of gravity' may elicit a much different meaning or understanding when heard by a student. A student might think of 'force of gravity' as identifying an entity that can be given to an object (such as a baseball). The force of gravity is thought by some students to be a force pushing down on objects. In *Making Sense of Secondary Science*, Driver et al. state: "Students believe objects are pushed down rather than pulled down by gravity." (Driver et al. 1994, 77) This perspective is pointed out by Clement, with a typical transcript from freshman engineering students concerning a coin tossed into the air: "So there's a force going up and there is the force of gravity pushing it down." (Clement 1982, 68).

As mentioned earlier, a lack of understanding of Newton's 3rd law appears to be a problem for some students with respect to gravitational forces. Students sometimes fail to realize that the earth attracts an object (such as a baseball falling) and the object (the baseball) attracts the earth.

Confusing acceleration with force is a problem for some students. diSessa and Sherin provide a specific example which illustrates how a student can confuse acceleration with the force of gravity. In their example a student treats the g, in F = mg, as the force rather than acknowledging F as the force. (diSessa and Sherin 1998, 1180) In an interview, the same student responds to a question about gravity as follows: "Gravity's uniform. So gravity won't pull any harder on something that's in the same place as it will on something else…" The student in this situation (interview reported by diSessa and Sherin) agrees that when holding an object, one feels something more or less directly.

"But she describes this as the weight of an object, and distinguishes it from the force of gravity." (diSessa and Sherin 1998)

Gravitational force always appears in pairs of equal forces acting on two bodies. Galili reminds us that "a question might arise 'which body's weight do we consider?' Newton would reply 'both'." (Galili 2001, 1082) With regard to two spheres Galili reminds us that during 1687, Newton wrote in his Proposition 8, Theorem 8 in Book III: "…the weight of either sphere towards the other will be inversely as the square of the distance between their centres." Seldom seen in textbooks is the Newtonian concept of reciprocal weight. When this is not mentioned there is a tendency to revert to the pre-Newtonian idea of gravity being "a primary quality, a characteristic of a single object, or in Galileo's view, a one-way downward pull. This pre-Newtonian understanding has become a common misconception of students." (Galili 2001, 1082) (See the rubric in chapter 3, Table 3-1, for references on gravitational force.) The rubric design includes a non-Newtonian way of looking at the description of gravitational force in Category 2A or 2B. It is interesting to note that Category 2 was the category indicated by the largest number of students when asked to describe gravitational force.

***What* do students think? (With respect to tension forces.)**

The term "tension" in a problem statement "often invokes confusion in the minds of students. Most have only a vague, undifferentiated sense of tension as both internal and external to the string. Since such confusion can impede future learning, it is desirable to make explicit the relationship between the tension in a string and the forces that the string exerts on the objects that it connects." (McDermott et al. 1994, 47) For example in research performed by McDermott et al. on student understanding of the Atwood's machine, the string played a prominent role in almost all the specific difficulties identified. In this research, students were expected to describe tension forces. The tension forces were used in writing some of the required statements (equations) using Newton's 2nd law of motion.

From other research, we find that many students do not recognize the existence of a so called "passive force", such as the tension in a string that adjusts itself in magnitude, in response to an applied force. For example, a survey was made in Norway of over 1000 students – upper secondary students, future teachers, university students, and physics graduate students. Students were asked to indicate forces on a stationary pendulum. Tension in the string was omitted by 50% of secondary students who had one year of physics, omitted by 40% of future teachers, and by 10% of graduate students. Students who had studied physics a short time and those who had studied physics for several years had similar problems.(McDermott 1984, 2) From this we could conclude that some misconceptions are hard to eliminate.

For this study, we expect that the misconceptions can be eliminated, but recognize that this change may be difficult to accomplish given the modest amount of instruction that is provided via the lecture, discussion, and lab sessions. The pre-post questions answered by the students are posed at the start of the lab session and at the end of the two hour lab session. During this short time interval, the probability that a misconception could be changed is not great.

What do students think with respect to normal forces?

The term normal force can easily register with a student as a term that means usual or ordinary, rather than the geometrical meaning of perpendicular. This sense has been observed in the research done in this study.

Confusion regarding the meaning of normal force, related to writing an equation using Newton's 2^{nd} law, could have been a source of difficulty for answering the pre-post questions in week three (for the cart moving up an incline). (See "Week 3 Lab Problem Description, Situation)

It is common for students to first encounter "normal force" in physics in a setting with an object, such as a rock, resting on a horizontal surface such as a table. In this special case, the normal force exerted by the table on the rock and the force exerted by the rock on the table are equal to mg, the weight of the rock. Students will sometimes just memorize the statement N = mg and use it when the normal force is requested. This means they will be using it incorrectly when an object is resting on an inclined surface. (Arons 1990)

How and why **do students think as they do? (With respect to gravity and other forces)**

As mentioned earlier, the force of gravity could be considered, by students, to be an entity which can be possessed, transferred, and dissipated (rather than an interaction). (Chi 2008, 71).

How do students think? Why do they think as they do? What are the ideas, information, and conceptions students bring to an introductory physics class? diSessa, Gillespie, and Esterly, investigate students' naïve physical ideas and discuss the question of whether naïve physical ideas are coherent or fragmented. These naïve physical ideas are sometimes referred to as uninstructed or at least non-normative ideas. They suggest "that a conceptual change approach should be helpful in understanding those ideas and their trajectory during instruction." (diSessa et al. 2004, 844). They consider these two perspectives – coherent vs. fragmented, to be consequential and contentious. One perspective considers naïve knowledge to be "coherent – even theory-like – and is *compactly characterizable."* "Compactly characterizable" means that relatively little needs to be said to describe a naïve theory or concept. (diSessa et al. 2004, 845). Ioannides and Vosniadou support the coherent view point in their paper on *The changing meanings of force*. (Ioannides 2001, 4)

Researchers with another perspective in the coherence versus fragmentation debate, "argue that naïve ideas are many, diverse, and not theoretical in any deep sense." (diSessa et al. 2004, 845). Minstrell talks about *facets* – relatively independent explanatory facts –

for example, “heavier things fall faster (because of their weight).” (Minstrell and Stimpson 1996). diSessa (1988,1993, 2004) talks about hundreds or thousands of inarticulate explanatory primitives (often referred to a as p-prims) which are activated in specific situations.

How **Do Students Think as They Do?**

The ‘***how*** do students think’ question might first be considered with respect to students formally studying physics for the first time. The two views on ‘coherence’ and ‘fragmentation’ that were previously discussed assume students come with ideas that provide a starting point for thinking about concepts. These starting points, the facets, the p-prims, the coherent, theory-like starting points might differ from student to student and might be far from the accepted canon of physics thinking. A student’s starting point will influence how and what they think and will be at least a part of why they think as they do.

Related to students’ starting point, as mentioned above, the matter of how students think and why they think as they do will be affected by their understanding of the nature of forces. As mentioned earlier when discussing ‘what students think’, Maloney comments: “What is conspicuously missing from students reasoning about forces is any concept of the ultimate nature of forces as interactions.” (Maloney 1990) Missing this understanding will certainly affect how students think about forces and provides insight into why they think as they do.

Considering again the starting point for student understanding, we look at work done by Chi and others on categorization – the assigning, by a person in an informal perhaps automatic sort of way, of a concept to the category to which it belongs. (Chi 2008, 71). According to ideas proposed and discussed by Reiner et al., concepts generally are classified by people into categories such as "entities" and "processes." Both of these categories can have subcategories; for example it is proposed that "processes" have subcategories: 'Direct' and 'Emergent'. If a student considers a concept to be in the 'Direct' subcategory, it would mean s/he automatically assigns properties and characteristics to the concept that would not be the same if s/he had assigned the concept to the 'emergent' subcategory. If the category to which the concept has been assigned is not the same as the one a physicist would use, it would mean the student has a perspective, with regard to the concept that could be quite different than the one held by a physicist. This could definitely raise problems for student understanding. (Reiner et al. 2000)

Continuing with an idea related to the 'student starting point', but more encompassing, we can consider *contextuality* presented by diSessa et al. "…*contextuality* concerns how students reason in different contexts." (diSessa et al. 2004, 849) "Students may well show several ways of thinking about a situation without any provocation….students may be primed by the way they happen initially to approach the problem or by the way questions are sequenced." (diSessa et al. 2004, 851). "…work by Anderson et al. (1992) suggests that whether one approaches a problem from the point of view of explanation or prediction may yield different results." (diSessa et al. 2004, 851)

When encountering certain words or terms, students may think of a context in a very different way compared with the context considered by the writer of a lab problem. For example, if a lab refers to *impulse* a physicist would think about $F_t = \Delta mv$; however, a student might think about 'doing something quickly in response to a stimulus'. The two sets of thoughts are related, but the student might be thinking about a type of verbal response or quick action taken by a person. The relationship, $F_t = \Delta mv$, could be far from or non-existent in the student's mind.

Many questions arise concerning understanding of concepts, problem solving, and the relationships among concepts, problem solving, and lab work. Are we talking about factors in learning and understanding that are closely linked or really separate with only superficial links? George Lakoff and Vittorio Gallese address some of these issues in a paper titled: "The Brain's Concepts: The Role of the Sensory-Motor System in Conceptual Knowledge." They propose that the sensory-motor system has the right kind of structure to characterize both sensory-motor and more abstract concepts." They tell us that: "Central to this picture are the neural theory of language and the theory of cogs (Contemporary Cognitive Science) according to which, brain structures in the sensory-motor regions are exploited to characterize the so-called "abstract" concepts that constitute the meanings of grammatical constructions and general inference patterns." (Gallese and Lakoff 2005).

Gallese and Lakoff propose what they call "a radically different view" as compared with a line of arguments of early cognitivism in which "…concepts are symbolic representations by nature, and as thinking, they can be reduced to symbolic (not neural) computation." They, "…argue that conceptual knowledge is embodied, that is, it is mapped within our sensory-motor system." They also, "…argue that the sensory-motor system not only provides structure to conceptual content, but also characterizes the semantic content of concepts in terms of the way that we function with our bodies in the world." A major finding in neuroscience is discussed by Gallese and Lakoff: "Imagining and doing use a shared neural substrate." For example, this means that imagining holding a glass and actually holding the glass use a shared neural substrate. (Gallese & Lakoff 2005, 456). Lakoff and Gallese make the hypothesis: "The same neural substrate used in imagining is used in understanding." (Gallese and Lakoff 2005). One might say these ideas suggest some basis for claiming that laboratory work should aid in the understanding of concepts and perhaps have some inherent link to problem solving.

It is clear from the literature that there are many reasons students respond as they do to ideas, concepts, and questions in physics. Now we look at changes, if any, of student skills in qualitative problem solving skills due to participation in lab sessions.

Chapter 3 Research Methods

Research Question

The research question investigated here considers students' qualitative analysis skill levels.

> **In what ways, if at all, do students qualitative analysis skill levels change in the domain of Newton's 2nd law and in the domain of**

gravitational force, from pre-test to post-test during a two hour lab period, and as measured during three successive lab periods, each of the lab periods being one week a part? For the purposes of this study, the qualitative analysis of a lab problem includes the physics and mathematical representation of a problem.

This chapter provides:

- An overview of the introductory physics course that was used for the study
- The population and the sample selection
- The process of developing the pre and post questions given during the lab sessions
- The development of the rubric used in analyzing the student descriptions of gravitational force
- A reliability assessment
- The role of the TAs
- The development of an instrument for observing and describing the handling of the lab sessions by the TAs
- Practices and Procedures followed by the TAs and students in the lab session. (General operation of the labs)
- Methods of data collection concerning TA teaching practices
- Observation scheme (check list of TA practices)
- Development of scheme for grouping results obtained from observations made of TAs

- Categories for Lab Teaching Guidelines

Overview of the Introductory Physics Course for Science and Engineering Majors

This is a descriptive study of introductory physics labs at the University of Minnesota. These labs are rather unique in that they are cooperative problem solving (CPS) labs. Each lab exercise in the lab manual has three or four problems. Students are usually assigned two problems, one week before the two hour lab session. The problems are in the form of a situation. As mentioned in chapter 2, students are asked to solve each problem so they can make a prediction concerning the problem situation. The students are to solve the assigned problems before the lab session. To aid in solving the problems, students are asked to answer some “warm-up questions” (or method questions). The answers to these “warm-up” questions are to be submitted to the TA during the day before the lab session. This allows the TA to obtain information about students’ understanding of the problems before the lab starts, so that the TA is in a better position to help/coach the students during the two hour lab session.

In the lab session, students work in groups of three comparing solutions or solving the problems, if they have not been successful before the start of the lab session. The solved problem provides a prediction. This prediction provides a basis for deciding, during the lab session, which measurements must be made to check their predictions. The students use computers and other lab equipment to make the measurements. They also write lab reports, about every two weeks, to report the results of one problem investigation performed during a two hour lab session.

The problem solving aspect of a lab problem has two main parts: qualitative and quantitative. The emphasis in this study is on the students' skills in the qualitative aspect of the problem solving.

Description of the Context

The Physics Course

The physics course used in the study was Physics 1301W, Introductory Physics for Science and Engineering I, which was conducted during the Fall semester of 2005. The course, which is the first introductory physics course, continues to be an important requirement taken by engineering and physical science students at the University of Minnesota Twin Cities campus. The online course guide described the course:

> This is the first of a three semester introductory course in physics for students in sciences and engineering.1301W/1302W, 2503 is designed to prepare you for work in your field by: building a solid conceptual understanding of real world applications based on a few fundamental principles of physics; practicing solving realistic problems using logical reasoning and quantitative problem solving skills; applying those physics concepts and problem solving skills to new situations; and learning to effectively communicate technical information. To achieve these goals, this course requires you to understand the material in depth. The emphasis will always be on the application of physics to real life situations and a large fraction of the problems will be designed to simulate such situations. 1301W will emphasize the application of physics to mechanical systems beginning with the description of motion of interacting objects and the forces that they exert on each other. Conservation ideas will also be used to describe the effect of interactions on systems of objects. A laboratory is included to allow you to apply both the concepts and problem solving skills taught in this course to the real world. It will also emphasize technical communications skills. A discussion section will give you the opportunity to discuss your conceptual understanding and practice your

> problem solving skills. This course assumes a background equivalent to high school physics and some familiarity with calculus.

Three major components comprise the course: lectures, labs, and discussion sessions. There were, during this study, three different lecture sections with a different professor teaching each section. Each instructional section consisted of about 260 students. Each professor presented three lectures per week.

Brief description of the nature of the lab sessions and the discussion sessions

In addition to the lectures, the students participated in a two-hour lab session each week and a one-hour cooperative problem solving session, called a discussion session (or recitation session).

During the lab sessions, students work in cooperative groups to solve a context rich problem. Context rich problems are problems designed within a context related to a real world setting. As mentioned earlier, students were expected to solve (or make an honest attempt to solve) the problems before the start of the lab session. Working as a group, the students were expected to devise a measurement plan after they arrived at the lab session. They used their measurement plan to check their solution to the problem. If students solved the problem correctly and made the correct measurements in the lab, they would be verifying the solutions they obtained.

The labs are not “cookbook labs” that provide specific ‘follow the recipe’ directions. The lab manuals are rather unique. As mentioned in chapter 2, the lab manual tells the students, “This laboratory manual is designed, in part, to help you recognize where your ideas agree with those accepted by physics and where they do not. It is also designed to help you become a better physics problem solver." (Heller and Heller 2005) A sample lab problem is provided in the Appendix.

The discussion sessions used the same type of context rich problems in a cooperative group setting. During the discussion sessions, students don't try to solve the problems before the discussion session and they don't check their solutions with computers and other lab equipment. They were in the same three member groups in the discussion sessions as in the lab sessions. Student groups were changed three or four times during the semester. Students were assigned to groups by the TA, following the guidelines suggested by Johnson & Johnson (Johnson et al. 1992) (Johnson et al. 1998).

Population and Sample Selection - TA's and Students

The population of students consisted of the students in Physics 1301W, described above. The TAs were assigned to the classes by members of the physics staff. The three professors were assigned to teach the classes by the administration.

Particular lab sections (including the TAs teaching the sections) to use as the sample were selected for this study on the following basis. Lab sections were chosen from two of the three professors at random. The sections were chosen at random from the ones that had complete sets of data and at least two observations by trained observers. The random selection process was continued until four lab sections with non-native English speaking TAs and four sections with native English speaking TAs were selected. Selection of both native and non-native English speaking TAs was used to minimize what might be considered an advantage for students with a native English speaking TA. There was an average sample population of 15 students per section, with a total sample population of 120 students.

Description of the Content Domain (Content of the labs being researched)

Each physics lab is built around a key concept or idea. For example, Lab III addresses the concept of 'Forces'. Seven or eight key concepts are examined in the lab sessions during a semester. Usually, two weeks are spent on each concept with the students solving two to four problems dealing with the particular concept for that Lab. Titles for the problems selected from the lab manual used in this study are identified below and the key concepts for the lab are indicated. A sample problem is also provided.

The lab problems used in this study were:

Lab 3 problem 1: **Force and Motion** (pre-post questions are related to this Lab problem)

Lab 3 problem 2: **Forces in Equilibrium** (pre-post questions related to this Lab)

Lab 4 problems 1&2: **Kinetic Energy and Work** (pre-post questions related to this Lab)

The pre and post questions used with these lab problems focused on descriptions of forces of gravity, tension, friction, and normal forces, with the main emphasis on the gravitational force. Newton's 2^{nd} law of motion was also a key factor in the pre and post questions used with these lab problems.

Figure 3-1 Example of a Lab Problem and Method Questions

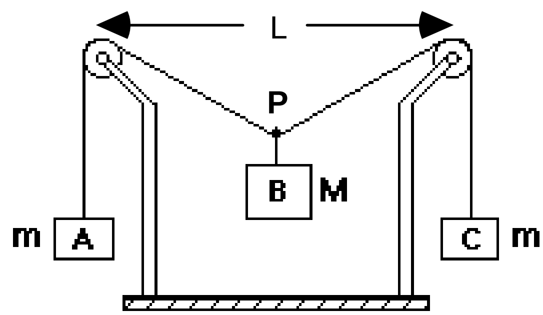
You have a summer job with a research group studying the ecology of a rain forest in South America. To avoid walking on the delicate rain forest floor, the team members walk along a rope walkway that the local inhabitants have strung from tree to tree through the forest canopy. Your supervisor is concerned about the maximum amount of equipment each team member should carry to safely walk from tree to tree. If the walkway sags too much, the team member could be in danger, not to mention possible damage to the rain forest floor. You are assigned to set the load standards.

Each end of the rope supporting the walkway goes over a branch and then is attached to a large weight hanging down. You need to determine how the sag of the walkway is related to the mass of a team member plus equipment when they are at the center of the walkway between two trees. To check your calculation, you decide to model the situation using the equipment shown below.

EQUIPMENT

The system consists of a central object, B, suspended halfway between two pulleys by a string. The whole system is in equilibrium. The picture below is similar to the situation with which you will work. The objects A and C, which have the same mass (m), allow you to determine the force exerted on the central object by the string.

You need to make some assumptions about what you can neglect. For this investigation, you will need a meter stick, two pulley clamps, three mass hangers and a mass set to vary the mass of objects.



PREDICTION

Predict the vertical displacement of the central object B in terms of quantities that you can directly control in the experiment. Use your equation to make a graph of the vertical displacement of object B as a function of its mass (M).

METHOD QUESTIONS

Read: Fishbane Chapter 4. Read carefully Section 4-6 and Example 4-12.

To solve this problem it is useful to have an organized problem-solving strategy such as the one outlined in the following questions. You should use a technique similar to that used in Problem 1 (where a more detailed set of Method Questions is provided) to solve this problem.

1. Draw a sketch similar to the one in the Equipment section. Draw vectors that represent the forces on objects A, B, C, and point P. Use trigonometry to show how the vertical displacement of object B is related to the horizontal distance between the two pulleys and the angle that the string between the two pulleys sags below the horizontal.

2. The "known" (measurable) quantities in this problem are L, m and M; the unknown quantity is the vertical displacement of object B.
3. Write down the acceleration for each object. Draw separate force diagrams for objects A, B, C and for point P (if you need help, see your text). Use Newton's third law to identify pairs of forces with equal magnitude. What assumptions are you making?
4. Which angles between your force vectors and your horizontal coordinate axis are the same as the angle between the strings and the horizontal?
5. For each force diagram, write Newton's second law along each coordinate axis.
6. Solve your equations to predict how the vertical displacement of object B depends on its mass (M), the mass (m) of objects A and C, and the horizontal distance between the two pulleys (L). Use this resulting equation to make a graph of how the vertical displacement changes as a function of the mass of object B.
7. From your resulting equation, analyze what is the limit of mass (M) of object B corresponding to the fixed mass (m) of object A and C. What will happen if M>2m?

EXPLORATION

Start with just the string suspended between the pulleys (no central object), so that the string looks horizontal. Attach a central object and observe how the string sags. Decide on the origin from which you will measure the vertical position of the object.

Try changing the mass of objects A and C (keep them equal for the measurements but you will want to explore the case where they are not equal).

Do the pulleys behave in a frictionless way for the entire range of weights you will use? How can you determine if the assumption of frictionless pulleys is a good one?

Add mass to the central object to decide what increments of mass will give a good range of values for the measurement. Decide how measurements you will need to make.

MEASUREMENT

Measure the vertical position of the central object as you increase its mass. Make a table and record your measurements with uncertainties.

ANALYSIS

Graph the *measured* vertical displacement of the central object as a function of its mass. On the same graph, plot the *predicted* vertical displacement.

Where do the two curves match? Are there places where the two curves start to diverge from one another? What does this tell you about the system?

What are the limitations on the accuracy of your measurements and analysis?

CONCLUSION

What will you report to your supervisor? How does the vertical displacement of an object suspended on a string between two pulleys depend on the mass of that object? Did your measurements of the vertical displacement of object B agree with your predictions? If not, why? State your result in the most general terms supported by your analysis.

What information would you need to apply your calculation to the walkway through the rain forest?

Estimate reasonable values for the information you need, and solve the problem for the walkway over the rain forest.

Physics for Science & Engineering, Mechanics Laboratory; Seventh Edition, University of Minnesota, School of Physics and Astronomy, 2005 by Kenneth Heller and Patricia Heller

The Nature of the Lab Problems

The labs follow a general pattern of: predict – explore – measure – explain. This approach follows ideas developed by Robert Karplus and others. (Karplus, 1980) The lab process starts with the student answering method questions (or warm-up questions) that are meant to provide a guide for making a 'prediction' about the lab problem. The prediction is really a solution to the problem the student is asked to solve. Solving these problems, as performed by an expert, would involve the use of qualitative analysis and quantitative problem solving. Novices will often try to proceed directly to the use of quantitative equations. (Larkin 1979). The labs are designed to promote the use of qualitative methods before proceeding to quantitative methods. Warm-up questions, and the exploratory part of the lab session, involve qualitative problem solving. The exploratory part includes trying different approaches to the problem and checking measurement results to find the general range of measurements that are possible with the available equipment.

Several suggestions are made in the lab manual that lead the student into exploration and, it is hoped, a better understanding of the concepts involved in the lab. As mentioned earlier, these lab problems are characterized as context rich problems. Each context rich problem requires qualitative analysis, which is the aspect of problem solving that is addressed in this descriptive study. (See the sample lab problem shown previously.)

The method questions (warm-up questions) answered by the students, are submitted to the TA during the day before the lab session, so the TA will have some idea about student understanding of the lab material before the actual lab session begins. As mentioned earlier, students are supposed to solve (or at least make an honest attempt at solving) the assigned problems before the lab session. During the lab session, students work in groups of three as they check their predictions by making measurements and by trying to explain them.

Obtaining Information about Students Qualitative Problem Solving Skills: Pre-Post Questions

Obtaining information about students' qualitative problem solving skills, and the possible changes in those skills, was investigated by analyzing responses to pre-post questions given at the beginning and end of each lab session. The time students spent responding to the questions was about 5 to 7 minutes at the beginning and at the end of each lab session. Questions were provided throughout the whole semester. About 800 students answered the questions. Only answers to questions posed during a three week period in the middle of the semester were used for analysis. The middle of the semester was chosen because, by that time, students were familiar with the types of questions and the routine of answering them. The middle of the semester is also deemed sufficiently far enough from the end of the term, so students were probably under less stress than they would be at the end of the semester, with up-coming final exams etc. Students were not graded on the pre-post questions and did not receive points for working on them. The TAs administered the written questions and returned them to the researcher at the end of each lab period.

Development of the Pre-Post Questions

The pre – post questions were developed over a five semester time period. They were new or reformulated each semester, and were used in pilot studies before the final semester in which the responses were used for analysis in this study. The answers to the pilot study questions provided insight into the ways students misinterpreted the questions, which statements were not clear, and in general which ones needed to be rewritten.

The pre – post questions used in this study are directly related to the problems the students solved in the lab sessions. This means the students were familiar with the context and general ideas posed in the questions.

The first part of the pre-post questions asked students to draw vector representations of forces on an object. These vector representations are useful for indicating student understanding of the forces (i.e., which forces and their direction and magnitude) involved in a problem. They are also useful in clarifying the written descriptions that are discussed below.

In another component of these pre-post questions, students are asked to solve for certain quantities. Solving an equation for a quantity is not really a part of qualitative analysis;

however, in this study it was often useful in gaining insight into the qualitative aspects of the student thought processes involved in problem solving.

The nature of the qualitative problem solving skills that are of interest in this study was illustrated in Figure 2-1.

Development of a Rubric for Analyzing the Student Descriptions of Gravitational Force

To analyze the data from the pre-post questions for gravitational force, a rubric was developed over an extended time frame using pilot studies and support from the literature. The author of this dissertation, and two other graduate students, worked with one of the author's advisors to rank written responses of students as they used qualitative analysis to solve physics problems. An understanding of the evaluation process from these pilot studies contributed to the development of the rubric used in the study described here.

Actual data from the current study, dealing with descriptions of gravitational force, were initially evaluated in an intuitive manner by ranking them on a scale of 1 to 7 (1 being the best, 6 the poorest, and 7 impossible to tell). [Different scales were used for different forces. For example, tension forces were ranked from 1 to 3.] The ranking process was performed with several sets of student responses. Generally, one set consisted of 30 papers (15 pre and 15 post questions and answers) representing the work of 15 students in one lab section, for one two hour lab period.

The ranking process was repeated with the same sets of papers after a time interval of 12 to 24 hours. Comparisons were made between rankings from the initial period and rankings completed 12 to 24 hours later. Rankings of some of the sets were also determined by a faculty advisor, with discussions among the three graduate students and the faculty member concerning the reasons for making ranking decisions.

Student responses were studied again, without reference to the initial ranking. Student responses were recorded and categorized, ranking them again from best to least satisfactory. Separate categories were used for each type of force, with gravitational force, tension force, normal force, and friction force categorized separately. The rankings from this process were compared with the rankings from the initial ranking process mentioned earlier.

The process of performing an initial ranking, followed by a subsequent ranking, proceeded toward the goal of developing a rubric which could be used to evaluate student answers for each force category. The categories in the rubric were developed based on student responses and the characteristics of the different forces as described in the literature. (See the references in the literature review (chapter 2) and in the rubric shown in Table 3-1 for gravitational force descriptions.) The results from using the gravitational rubric have been an important part of this study. It should be noted that the student responses to requests for description of the forces – tension, friction, and normal – are not specifically reported separately in this study. The ideas related to these three types of forces are, however, related indirectly to students' responses concerning Newton's 2nd

law of motion. Student responses to questions concerning Newton's 2nd law of motion played an important role in the overall analysis of qualitative problem solving skills.

The rubric used to classify students' descriptions of gravitational force is shown below in Table 3-1. Comments, with references, provide information about the nature and meaning of each particular category and provide rationale for including particular student answers in a certain category.

Categories of Students' Responses (Includes references concerning nature of forces)

A Rubric for Categorizing Student Responses for Gravitational Force

Table 3-1 Gravitational Force

General concept and Written explanations	Reference related to concept and explanations (Some student e.g.s)	Diagrams	Background
(1) Forces are caused by the interaction of an object with another object. (e.g., Attraction between earth and object, or Pull of earth on object)	The Physics Teacher, Sept. 1990 Maloney, D. P. (1990). Forces as interactions. *The Physics Teacher*, 386-390. The Physics Teacher, Feb. 1991. When Words Fail Us by Jerold S. Touger: "The physicist thinks of forces as actions – more specifically as interactions – " p91.	I. Force as a pull	Forces are caused by the interaction of an object with another object. [In particle physics forces are described as arising from the exchange of objects called *gauge bosons*; (or sometimes referred to as exchange particles)] (Nature of force in particle physics by J Allday.)

General concept and Written explanations	Reference related to concept and explanations (Some student e.g.s)	Diagrams	Background
(2A) Gravitational Force; Force of gravity; Force due to gravity(note: for correct usage, avoid force *due to* gravity; use gravitational force)(See TPT Feb. '91,Touger) (Might indicate a force caused by interaction of an object with another object – but is not clear if that is the meaning.)	For some students the force of gravity could be considered an *entity* which can be possessed, transferred, and dissipated (rather than an interaction). Chi, Handbook of Research on Conceptual Change. Vosniadou (Ed.) 2007 p20. [force of gravity; force due to gravity gravity acting on cart; gravity pulling on cart] [Student e.g.s "F_w =gravity pulling the cart down (weight force);" "mg = gravity force;"]		Physics novices might think of gravity as the potential of all material objects to fall. (Reiner, Slotta, Chi, and Resnick, p12; 2000)
(2B) Weight of object (Could indicate the force of gravity or might suggest weight is a property of the object.)	Some students might consider that "Weight is an intrinsic property of an object (even though gravity is conceptualized as an external factor that pulls harder on heavier objects)." Chi, Handbook of Research on Conceptual Change. Vosniadou (Ed.) 2007 p20.		Novices, not possessing the concept of a gravitational field, "tend to explain this unique supply of force by assuming an innate, inexhaustible internal property called weight. Every object will naturally fall down under the force of its own weight." (Reiner, Slotta, Chi, and Resnick, p12; 2000)

General concept and Written explanations	Reference related to concept and explanations (Some student e.g.s)	Diagrams	Background
(3A) Gravity considered a separate entity within or outside of the object that is being pulled by the earth. Its numerical value is determined by 'mg'. Students here are probably not thinking of the force as an interaction between two objects. (Student thinking could suggest gravity is a property of an object.) Student expressions: Force of weight; F_g = pulls down on cart/object, ($F_N = F_g$); mg = force of gravity of A; pull of gravity of the cart; F_g = gravity =mg; mg = weight force of the cart mg = gravity	Again for some students the force of gravity could be considered an *entity* which can be possessed, transferred, and dissipated (rather than an interaction). Chi, Handbook of Research on Conceptual Change. Vosniadou (Ed.) 2007 p20. Reiner, Slotta, and Chi hypothesize that "physics novices tend to associate abstract concepts with a well-instantiated substance schema." (Note the 'substance' idea here which according to students often refers to weight as separate from a gravitational field.) "Novices have a definite conception of weight in their substance schema that has nothing to do with the gravitational field as defined by physics." Reiner, Slotta, & Chi, Naïve Physics Reasoning, Cognition and Instruction p 13, 2000		

General concept and Written explanations	Reference related to concept and explanations (Some student e.g.s)	Diagrams	Background
(3B) “Push of gravity” F_g: gravity opposite of normal force	“Students believe objects are pushed down rather than being pulled down by gravity.” Driver, R., Squires, A., Rushworth, P., & & Wood-Robinson, V. (1994). *Making sense of secondary science: Research into children’s ideas.* . (pp. 77). New York, NY: Routledge. A typical transcript from freshman engineering students concerning a coin tossed into the air: “So there’s a force going up and there is the force of gravity pushing it down.” John Clement, Am. J. Phys., p68, (1982)		

General concept and Written explanations	Reference related to concept and explanations (Some student e.g.s)	Diagrams	Background
(4A) Newton's 3rd law problem (Students fail to realize that earth attracts an object and the object attracts earth.)	C. Terry and G. Jones, "Alternative frameworks: Newton's third law and conceptual change," Eur. J. Sci. Ed. 8, 291 (1986) Terry and Jones suggest that students "do not have an understanding of the concept of force and interaction – they do not understand that forces arise from interactions between two objects or that the forces involved in the interaction can be described by the third law. There was no indication that pupils generally think of an interaction in terms of an equal and opposite pair of forces. Yet such an understanding is central to an understanding of the overall concept of force."		[Student e.g. mg = push of cart on the table due to gravity]
(4B) Acceleration confused with force of gravity; Weight due to g	VI "g" used to identify force of gravity "g" identified as a force rather than "F" diSessa, Sherin, What changes in conceptual change? Int. J. Sci. Educ p 1180; (1998) ["A different coordination for force than a physicist"(coordination class)] Some students treat "mg" as an acceleration, not a force		

General concept and Written explanations	Reference related to concept and explanations (Some student e.g.s)	Diagrams	Background
(5A) Only provides definitions of variables either correctly or incorrectly (e.g. mg = mass x gravity; F = mass x gravity; F_w = weight (mass x gravity). No real description of the force.	student e.g.s: F_g pulls it down; $m_c g$ = mass & gravity		
(5B) Can't tell (may be nonsensical)			
(6) Other Descriptions and/or diagrams not included in above categories			

Summary form of the rubric on gravitational force

The previous rubric, in Table 3-1, is shown in 'descriptive label' form in Table 3-2 with descriptive labels for the categories. These descriptive labels are expanded in Table 3-3.

Table 3-2 Categories for Gravitational Force

Category 1: (Gravity interaction)	Category 2: (Force or weight)
Category 3: (Entity or push)	Category 4: (3rd law problem or gravity vs. acceleration)
Category 5: (Definitions or can't tell)	Category 6: (Other)

Table 3-3 Expanded Descriptive Labels

Rubric: Categories of Students' Responses **Categories 1; 2A & 2B = 2; 3A & 3B = 3; 4A & 4B = 4; 5A & 5B = 5; 6**
(1) Gravitational interaction between two objects
(2A) Gravitational Force; Force of gravity; Force due to gravity
(2B) Weight of object
(3A) Gravity considered a separate entity within or outside of the object that is being pulled by the earth. Student expressions: Force of weight; F_g = pulls down on cart/object, ($F_N = F_g$);
(3B) "Push of gravity"; F_g: gravity opposite of normal force
(4A) Newton's 3rd law problem (Students fail to realize that earth attracts an object and the object attracts earth.)
(4B) Acceleration confused with force of gravity; Weight due to g
(5A) Only provides definitions of variables either correctly or incorrectly
(5B) Can't tell (may be nonsensical)
(6) Other Descriptions and/or diagrams not included in above categories

Inter-rater reliabilities for use of the rubric (See Table 3-4)

Inter-rater reliabilities for use of the rubric were determined by evaluations of student responses, as determined by three evaluators. The evaluators were two graduate students (one in physics and one in science education) and the author of this dissertation. A series student response sets were evaluated by each of the three participants. Each set consisted of 25 to 32 pre and post questions and associated student responses. The response categorizations were compared and discussed by the three participants. After the comparisons and discussion, another set of papers was evaluated by the participants. This process was repeated until a consensus was reached on the categorization process.

Development and application of the rubric provided a six category, non-parametric ranking rubric. (See Table 3-1, Table 3-2 and Table 3-3) Data from the study indicated that a six category rubric provided categories with a larger sample population (N), which is useful for gaining information from the data.

Table 3-4 Inter-rater Reliabilities for the Rubric Used to Rank Qualitative Problem Solving (Agreement Between Evaluators When Using a Rubric for Evaluating Student Responses)

Gravity			
Lab. 3 Prob. 1	Sec. 120, N = 22	Eval.1vs Eval. 3	91% agreement
	Sec. 120, N = 22	Eval. 2 vs Eval. 3	91% agreement
	Sec. 145, N = 30	Eval. 1 vs Eval. 3	90% agreement
	Sec. 145, N = 30	Eval. 2 vs Eval. 3	90% agreement
Lab. 3 Prob. 2	Sec. 108, N = 28	Eval. 1 vs Eval. 3	93% agreement
Lab. 4 Prob. 1&2	Sec. 133, N = 30	Eval. 2 vs Eval. 3	83% agreement
	Sec. 133, N = 30	Eval. 1 vs Eval. 3	83% agreement
Tension			
Lab. 3 Prob. 1	Sec. 120, N = 22	Eval.1 vs Eval. 3	100% agreement
	Sec. 120, N = 22	Eval.2 vs Eval. 3	91% agreement
Normal			
Lab. 4 Pr 1&2	Sec. 114, N = 30	Eval.1 vs Eval. 3	93% agreement

Friction			
Lab. 4 Pr 1&2	Sec. 133, N = 30	Eval.1 vs Eval. 3	93% agreement
	Sec. 133, N= 30	Eval.2 vs Eval. 3	93% agreement

Evaluating the use of Newton's 2nd law of Motion

The student responses for Newton's 2nd law of motion were evaluated as correct or not correct. There are, of course, many ways of incorrectly writing the sum of forces using Newton's 2nd law. Determining a rank of incorrectness was not attempted because it is very difficult to obtain agreement on such a ranking scale. Table 3-5 provides examples of incorrect student responses and a correct student answer. Table 3-6 identifies the level of agreement between evaluators when evaluating the use of Newton's 2nd law.

To remove bias when evaluating the papers using a rubric, the evaluators did not know which papers were pre and which were post. The evaluators also did not know the student names, the TA names, or names of the professors for the papers they were evaluating.

Table 3-5 Newton's 2nd Law
From Pre-Post Question Set 3 (Week 3)

Examples of Incorrect Student Responses	A correct student answer
1. $F_f + F_p$ = ma, where F_f = friction force and F_p = vector related to F_f and F_N (where F_N = force normal)	$\Sigma F_x = F_f + mg \sin\theta = ma$; where F_f = friction force
2. $\Sigma = F_r + F_N + mg + F_g$; where F_r - the cart rolling force; F_N – the normal force act on the cart; mg – the gravit (*sic*) force act down on cart; F_f friction force	$\Sigma F_x = F_f + mg \sin\theta = ma$; where F_f = friction force
3. F_{total} = ma – F_f ; F_N = force normal; F_w = force weight; F_f = force friction [F_N, F_w, and F_f were drawn approximately correct (F_w drawn straight down from center of cart)]	$\Sigma F_x = F_f + mg \sin\theta = ma$; where F_f = friction force
4. $F = \mu mg \sin\theta$	$\Sigma F_x = F_f + mg \sin\theta = ma$; where F_f = friction force

Table 3-6 Agreement Between Evaluators When
Evaluating the Use of Newton's 2nd Law

Newton's 2nd law			
Lab 3 Prob. 1	Sec 108, N = 56	Eval.4 vs Eval 3	89% agreement
	Sec 135, N = 64	Eval.5 vs Eval 3	91% agreement

The Role of the TAs in the Lab Sessions

TAs in charge of the lab sessions play a significant role in the student's laboratory experience. The goal "is to provide students with practice solving problems using a logical, organized problem solving process." (Heller et al. 2005) As previously mentioned in chapter 2, the lab functions are based on a cognitive apprenticeship model. TAs play an important role in providing guidance to students by initially "coaching" them, then "fading" as students gain confidence working as an independent group. (Brown et al. 1989; Farnham-Diggory 1994; Heller et al. 1992; Heller and Hollabaugh 1992).

Development of the TA Observation Scheme (Observers Check List)

TAs were observed when they were teaching the labs so that information could be obtained about the teaching strategies and methods that were used. Without this information, we would not have had a proper sense of what the TAs were doing and what the TAs asked the students to do. These factors may have had a significant impact on how the students responded to the pre-post questions.

General Operation of Labs

The cognitive apprenticeship model provides a basis for the teaching strategies in the TA guidelines. The first part of the actual lab session is called "Opening Moves." It includes answers to TA selected Warm-Up Questions, which are written on the board by students. The TA then leads a 5-10 minute discussion of the student responses to the Warm-Up Questions. The TA should not confirm correct answers to the actual lab problem at the beginning of the lab, but should raise questions for the students to consider when performing the lab. The students should then use the lab time to find/confirm the answer(s) to the lab problems.

In the second part of the lab session, called the "Middle Game", students perform the lab work. The TA listens to and observes the groups of students, providing coaching for students as their needs become evident. Based on their predicted solution, measurements made, and the problem solving done in lab, the students are to reach a conclusion about their problem solution during this time.

In the last part of the lab, called the "End Game", the TA selects one person from each group to write results on the board, then leads a class discussion for about 10 minutes, focusing on key aspects of the physics concept students were to learn from solving the lab problems. The entire lab session lasts two hours.

An Outline of Cooperative Problem Solving (CPS) Teaching Practices for Labs is shown in Figure 3-2. This outline is from the Instructors Handbook A Guide for TAs (Heller et al 2005) which was developed by the Physics Education Research (PER) group at the University of Minnesota. The outline provided guidelines that were essential for the development of the TA observation scheme in Figure 3-3. Over a time span of four semesters, the observation guide was developed with the aid of 12 different observers, including elementary education majors working as TAs in a physics class at the University of MN.[3] This particular physics class, Physics 3071 – Laboratory-Based Physics for Teachers, is designed for elementary education majors. The elementary education majors working as TAs in Physics 1301W have already taken the class.

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3 Physics 3071 is a course with a guided inquiry approach and an emphasis on students developing, as a class, their own writing of the basic principles. The class work involves predictions, problems to be solved, experiments to check on ideas, and simulations to confirm ideas and provide help in understanding physics principles.

Figure 3-2 Outline of Cooperative Problem Solving (CPS) Teaching Practices for Labs

Before-teaching Checklist

- ❑ assign new roles (and groups when appropriate)
- ❑ solve *Methods Questions* to arrive at *Prediction*
- ❑ review comments and suggestions in *Lab Instructor's Guide*
- ❑ grade Methods Questions; decide which Methods Questions to have groups put on board
- ❑ □□□□□.pre-lab scores (when appropriate)

	Instructor Actions	What the Students Do
Opening Moves ~15 min.	⓪ Be at the classroom early ① Prepare students for group work by showing group/role assignments. ② Prepare students for lab by: a) diagnosing difficulties while groups discuss and come to consensus on *Methods Questions*; select *Methods Question(s)* to have groups put on the board. b) selecting one person from each group to write/draw on board answers to your selected *Methods Questions*. c) leading a class discussion about the group answers (without telling them the answer). d) telling students how much time they have to check their predictions	• Students move into their groups. • Work cooperatively. • Write on board. • Participate in class discussion.
Middle Game (depends on problem)	③ Coach groups in problem solving (making decisions) by: a) monitoring (diagnosing) progress of all groups b) coaching groups with the most need. ④ Grade Lab Procedure (journal). ⑤ Prepare students for class discussion by: a) giving students a "10-minute warning." b) selecting one person from each group to put corrected *Methods Questions* and results on board.	• Check their group prediction by: - exploring apparatus - deciding on measurement plan - executing measurement plan - analyzing data as they go along - discussing conclusions . . . • Finish work on lab problem • Write on board

	Instructor Actions	What the Students Do
End Game ~10 min.	⑥ Lead a class discussion focusing on what you wanted students to learn from solving the lab problem (usually related to *Methods Questions*). ⑦ Start next lab problem (repeat Steps 1 – 7) ⑧ At end of session, assign next week's lab problems; assign Lab Reports (if last week of lab)	• Participate in class discussion • Participate in class discussion

Video tapes were made of some lab sessions that were part of this study. Observing these tapes helped the process of developing the observation guide check list. During four semesters, observations were performed using pilot forms of the observation scheme check list. Discussions with the observers followed observations in the labs, using the particular scheme du jour. With this process, the observation scheme evolved to the scheme used in the semester during which data was taken for this study (see Figure 3-3).

Methods of Data Collection Concerning TA Teaching Practices

Data on the TA teaching methods and practices were collected by observers using the observation check list shown in Figure 3-3. Observers recorded information about key elements of TA teaching practices on the Observer's Check List during the entire two hour lab period. Each TA in the study was observed, at random, from one to three times during the semester. All observers conducted their observations during two to three lab sessions. During each session, another independently functioning observer also recorded information to facilitate inter-rater reliability checking. Observer agreement on key aspects of the observations varied from 91% to 100%.

Information concerning the actual use of lab session instructional methods and strategies by the TAs in the lab sessions was obtained from the pool of observers mentioned above. Other observers included Ph.D. students in Science Education, a post-doc in PER, and the author of this dissertation.

Figure 3-3 Observation Scheme

Observers' Check List

Day_____ Date________ Time________ Name of Observer_______________________________
Lab section #_________ # Students in lab______ Room #________ TA___________________________
Lab #_______ Problem #______

OPENING MOVES	**Actual Start Time:** ___________	**Comments**
⓿ TA is prepared at scheduled class time ❶Prepare students for group work by showing role assignments. (~ 1 minute) (Time spent on "Pre" questions)	☐TA prepared on time ☐TA provides role assignments _______ minutes spent on Pre questions	(Note: If the TA performs the task make a check ✔ in the box ☐ if not, cross out the words after the box.)
❷Prepare students for lab by: a) Telling students: (1) Which Method Question(s) to discuss and put on the board (2) What aspect of problem solving they should learn in the lab	☐ Telling students MQs to discuss and put on board. ☐Aspect of prob. solving	(Mention what goes on if different than what is suggested on this form.)
b) Diagnosing difficulties while groups discuss and come to consensus on answers to *Method Questions*. (~ 5 minutes)	☐Discussing in small groups for ______ minutes ☐ TA walks from group to group listening /watching what groups are doing for ________ minutes	
c_1) TA selects one person from each group to write/draw on board answers to TA selected *Method Questions*. c_2) Students put group answers on the board. (~ 2 minutes)	(Choose one of the next two) ☐TA selects students to write on board ☐Students self select person to write Time putting up answers ______min.	(What does the TA do if he/she does not have students put answers on the board?)
Make-up of groups: Indicate the group make-up according to sex –(e.g. Grp 1: 1 M, 2 F)	Grp 1 ___M, ___F; Grp 4 ___M, ___F Grp 2 ___M, ___F; Grp 5 ___M, ___F Grp 3 ___M, ___F; Grp 6 ___M, ___F	(Note: Observer should draw a sketch of the tables with groups and give numbers 1, 2, 3 …. to the groups.)

Development of scheme for grouping the results obtained from observations of the TAs

To use the information obtained from observations of the TAs, the results were grouped into categories. The major work in developing the categories for Table 3-7 was accomplished over four semesters when, as described above, the observation form was being developed. The grouping of the results into categories, obtained from the observations of the TAs, was informed by the guidelines suggested for the TAs in the Lab Instructor's Handbook. (Heller et al. 2005). See Table 3-7 for the categories that were developed as lab teaching guidelines. These categories were used to obtain information about the nature of the lab teaching practices used by the TAs.

Table 3-7 Categories for Lab Teaching Guidelines

A. Students put Method Questions on board (under direction of the TA)
B. Leading Class Discussion
C. TA does not give a lecture about the lab
D. TA asks questions while working with whole class
E. Method Question answers not confirmed by TA at START of lab session
F. Time for class discussion at start of lab
G. Students start working with equipment a short time after lab session starts
H. TA coaches groups
I. TA interacts with all groups during each 10 minute interval
J. Students put lab results and/or method question answers on board
K. TA leads class discussion near end of lab session
L. TA does not give a lecture on lab topics near end of lab session
M. TA asks questions of individuals during whole class discussion

Chapter 4 Results

Overview

The main focus of the study is to investigate the effectiveness of the Cooperative Problem Solving (CPS) labs, in terms of students' qualitative analysis skills, with respect to CPS lab problems. Students were required to solve a problem in writing before the lab session. Then, they investigated the validity of their answer using lab equipment, while working as a cooperative group of three students. During the lab, the students were provided with a physical situation that was the same as the one described in their written problem. For this study, students were asked questions about the written problem in the context of the physical situation.

During both the first and second week of the study, students were asked two sets of pre-post questions related to gravitational force and two sets of pre-post questions related to Newton's 2nd law. During the third week, students were asked two pre-post questions related to gravitational force and one pre-post question related to Newton's 2nd law. The pre-tests were identical to the post-tests.

The student pre and post answers to the questions were analyzed to provide insight into student qualitative analysis skills. Student descriptions of Newtonian gravitational force were to be initially classified using a rubric with ten different categories, as described in chapter 3. However, experience with using the 10 category scheme strongly suggested combining some of the ten categories to form a six category scheme. This increased the numbers of responses in some categories and provided more reliable assessments of the students' responses to the questions. The resulting category scheme is shown in Table 3-2 and is expanded and shown in Table 3-3.

The responses to the requests for the sum of forces, using Newton's 2nd law of motion, were categorized as either correct or incorrect. Using a ranking scale to describe the correctness of the student responses did not lend itself to consistent evaluations. The majority of the incorrect responses were either incorrect for the same reasons or could not be ranked because the correctness of one answer, when compared with another, was inconclusive.

Research Question

The central question of this research was concerned with students' qualitative analysis skill levels. The question was:

> **In what ways, if at all, do students qualitative analysis skill levels change, in the domain of Newton's 2nd law and in the domain of gravitational force, from pre-test to post-test during a *two hour lab period, and as measured during three successive lab periods each of the lab* periods being one week apart? For the purposes of this study the qualitative analysis of a lab problem includes the physics and mathematical representation of a problem.**

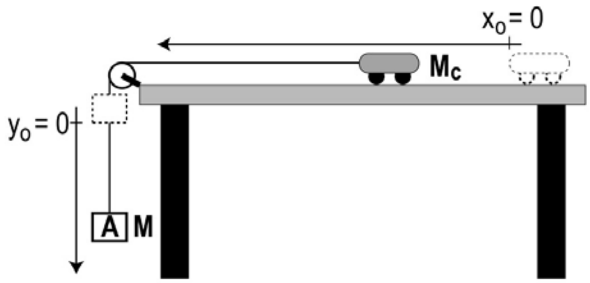
Weekly Lab Problems and Pre-Post Questions

As described in chapter 3, students used a different laboratory situation (i.e., lab set-up) each week. For each of the three situations, they were asked pre-post questions related to gravitation and pre-post questions related to Newton's Second Law. The lab problems, on which the pre and post questions are based, are found in the University of Minnesota Lab Manual (Heller and Heller 2005). Week 1: Lab 3 problem 1; Week 2: Lab 3 problem 2; Week 3: Lab 4 problems 1 & 2. The three situations and questions are identified below.

Week 1 Lab Problem Description

Situation

An accelerating, frictionless cart on a table is being pulled by a light cord that extends over a pulley and then down to an Object A (mass M). (See diagram below.)



Pre and Post Gravitation Questions

Describe in words, each force acting on the cart and each force acting on Object A (mass M). (See diagram above.)

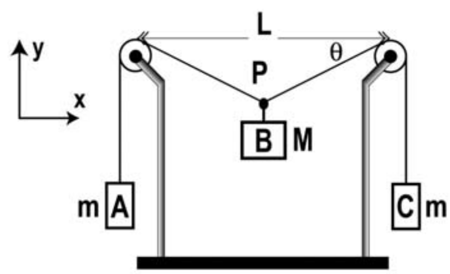
Pre and Post Newton's 2nd Law Questions

Write Newton's Second Law ($\sum F = ma$, where "$\sum$" means the sum of the forces) for the cart, (in the x direction), and for Object A, (in the y direction).

Week 2 Lab Problem Description

Situation

A central object B is suspended halfway between two pulleys by a light string.



Pre and Post Gravitation Question

Describe in words each force acting on Object B, and each force acting on point P. (See diagram above.)

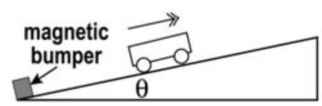
Pre and Post Newton's 2nd Law Questions

Write the vertical (y) component of Newton's Second Law ($\sum F_y = ma_y$, where "$\sum$" means the sum of the forces) for Object B, and for point P.

Week 3 Lab Problem Description

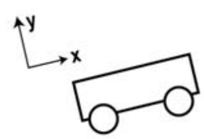
Situation

A cart (mass m) is released, rolls down a ramp, collides with a magnetic bumper, and then rolls back up the ramp. (The pre-post questions deal with the cart rolling up the ramp.) (See diagram below.)



Pre and Post Gravitation Questions

Describe in words each force that is acting on the cart as it rolls up the ramp.



Pre and Post Newton's 2nd Law Questions

Write the x-coordinate component of Newton's 2nd law ($\Sigma F_{x} = ma_{x}$, where"Σ" means the sum of the forces) for the cart rolling up the ramp.

Results for Gravitation Questions

Revised Scoring Rubric

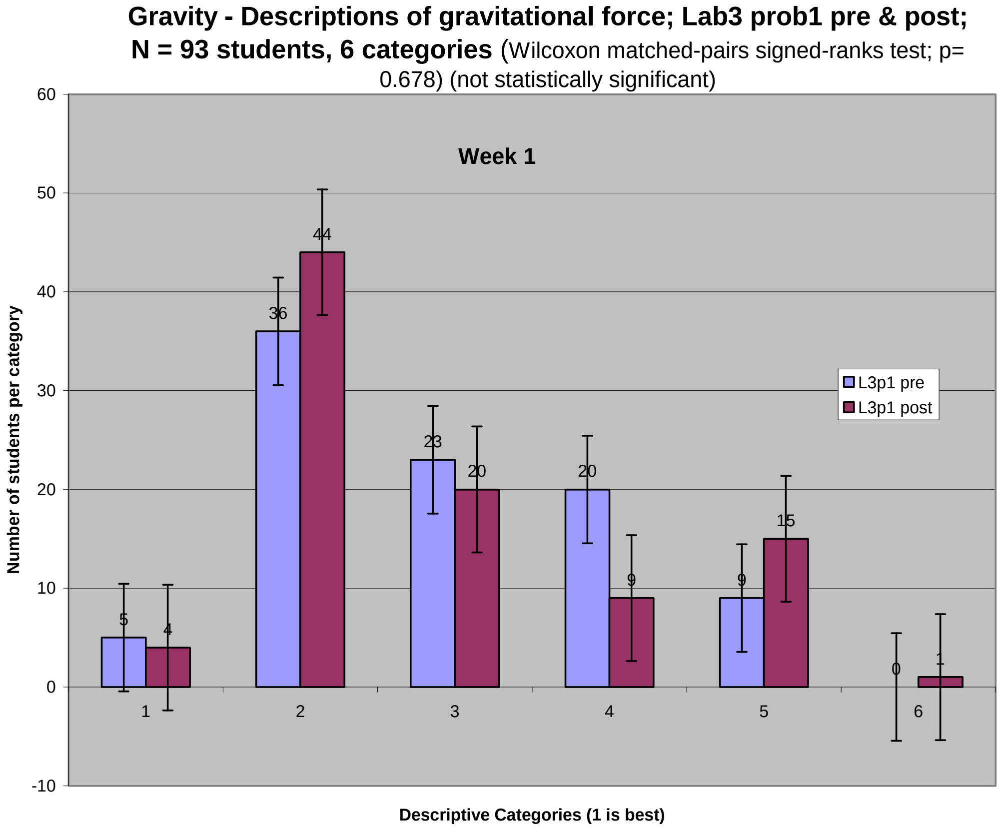
A revised rubric for ranking the descriptive responses concerning gravitational force is identified in Table 3-1 in chapter 3. Condensed versions of the six categories are: (1) Gravity interaction, (2) Force or weight (3) Entity or push (4) Gravity vs acceleration, (5) Definitions or can't tell, (6) Other. Descriptive labels for the categories in the rubric are located in Table 3-2. Expanded descriptions are located in Table 3-3.

Week 1 Results for Gravitation

In week 1, an accelerating, frictionless cart on a table is being pulled by a light cord that extends over a pulley and then down to a mass M. Students were asked to describe the forces acting on the cart and on object A. Their responses to both parts of the question (regarding the cart and Object A) were analyzed together to assess their understanding of gravity.

Analysis of the pre-test post-test results using the Wilcoxon matched-pairs signed-ranks test shows no statistically significant difference between the pre and post results. ($z = 0.415$, $N - Ties = 38$, $p = 0.678$, two tailed). It is evident in Figure 4-1 that Category 2 (force or weight) has the largest number of responses (pre-test = 36% and post-test = 44%). The students in this category described the force as a gravitational force, or force due to gravity, or weight. However, they did not write about the interaction of two objects or a gravitational attractive interaction between two objects.

Figure 4-1 Descriptions of Gravitational Force
Number of Students Responding in Each Category for Gravitational Force in Week 1 (N = 93)

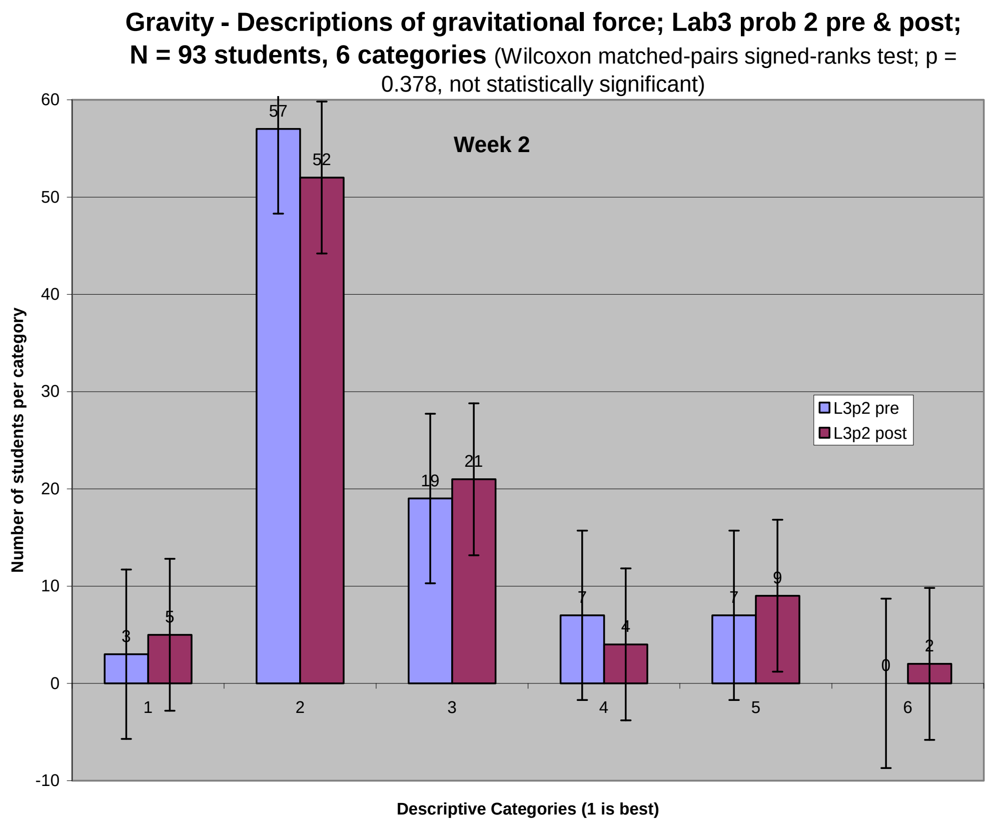


Week 2 Results for Gravitation

In week 2, a central object B is suspended halfway between two pulleys by a light string. Students were asked to describe each force acting on Object B, and each force acting at the point on the string from which the Object B is suspended (Point P). The results from object B and point P were analyzed together, to assess students' understanding of gravity. The results are described in Figure 4-2.

From the graph for week 2 in Figure 4-2, we see that the largest number of responses is again in Category 2 (force or weight). Again, the statistical evidence from the Wilcoxon matched-pairs signed-ranks test for this graph does not allow us to conclude that the difference between the pre and post scores is statistically significant. (z = 0.882, N - Ties = 31, p = 0.378, two tailed)

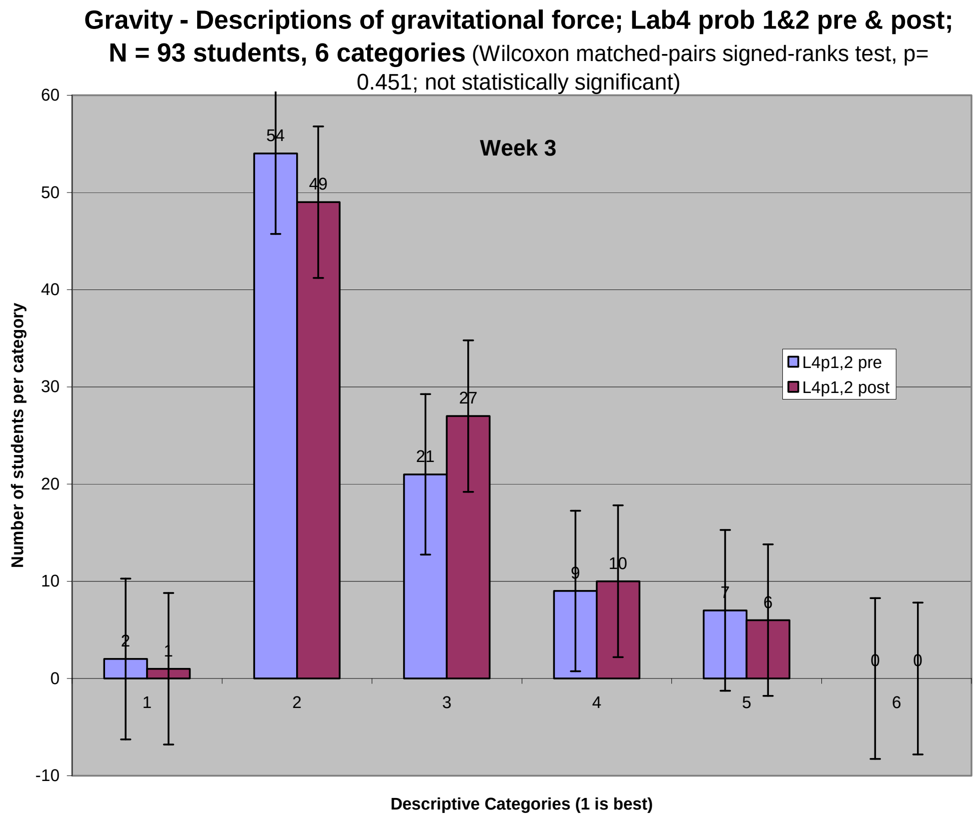
**Figure 4-2 Descriptions of Gravitational Force
Number of Students Responding in Each Category for
Gravitational Force in Week 2 (N = 93)**



Week 3 Results for Gravitation

The next graph, Figure 4-3, continues the general pattern observed in the other graphs. The most common student response is again Category 2. The students in this category described the force as gravitational force, or force due to gravity, or weight. They did not talk about the interaction of two objects or a gravitational attractive interaction between two objects. Again, the statistical evidence from the Wilcoxon matched-pairs signed-ranks test for week 3 does not allow us to conclude that the difference between the pre and post scores is statistically significant. (z = 0.755, N - Ties = 31, p = 0.451, two tailed)

Figure 4-3 Descriptions of Gravitational Force
Number of Students Responding in Each Category for Gravitational Force in Week 3 (N = 93)



Summary comments – patterns for gravitation

The statistical tests of the data for each of the three weeks were not statistically significant. There was no discernable change in the students' qualitative analysis skills from pre-test to post-test. We note some information about the change, or lack of change, from pre to post for questions about gravitational force. Here we consider all six categories simultaneously, not each of the six categories separately.

In week 1, 59% (55 out of 93) of the responses about gravitational force did not change from pre to post. 19% of the pre responses (18 out of 93) changed to a worse category and 22% (20 out of 93) changed to a better category. In week two 67% of the pre to post responses (62 out of 93) remained the same, 14% improved and 19% changed to a less correct category. In week three 67% (62 out of 93) remained the same, 15% improved and 18% got worse.

Next we look at individual categories to see how students in a particular pre-test category remained the same, improved or got worse on the post-test. In addition to the statistical analysis, the shifts of students' responses from one category on the pre-test to another category on the post-test were tracked. This was done because the statistical analysis alone would not reveal if the same students were staying in the same categories or if different students were ending up with responses in different categories. For example, it was possible that some number of students, say 30% who began in Category 2, had changed to another category and been replaced with the same number of students who had changed from other categories to Category 2 on the post-test. If this occurred, the same number of students would be in Category 2 on the pre-test and post-test, but the students would have been different people. The stability of students' responses from pre-test to post-test was assessed in this way. What is reported below is only for students who began in the optimal Category 1, or in categories where there were more than 20%

(18) of the initial 93 students. The other categories did not contain enough pre-test responses to see if there were any shifting patterns of responses.

For Question #1

Five students (5.4%) began in Category 1, which was an optimal response. Three (60%) of those students remained in the same category and two of the students (40%) changed to a less favorable category for the post-test.

Thirty-six students (39%) began in Category 2 and 27 (75%) of them remained in Category 2. One student (2.8%) changed to the more favorable Category 1 and eight (22.2%) changed to a less favorable category.

Twenty-three students (24.7%) began in Category 3. Twelve (52%) remained in the same category. Six (26%) changed to the more favorable but not optimal Category 2. None changed to Category 1, the optimal category. Five (21.7%) changed to a less favorable category.

Twenty students (21.5%) began in Category 4. Seven (35%) of the students remained in Category 4 and ten (50%) changed to a better category. Of the ten that changed to a better category, eight changed to Category 2, a more favorable category. Two changed to Category 3, which is not very good, but better than Category 4. None changed to the optimal Category. Three students out of 20 changed to Category 5. (Note: This Pre

Category 4 contains more than 20% of the starting number of students so results for Category 4 are included here.)

For Question #2

Three students began in the optimal Category 1. Two (66.7%) of those students remained in the same category and one of the students (33.3%)changed to a less favorable Category 2.

Fifty seven students (61%) began in Category 2 and 43 (75.4%) of them remained in Category 2. Three (3.2%) went to the more favorable Category 1 and eleven (19.3%) went to a less favorable category.

Nineteen students (20.4%) began in Category 3 and ten of nineteen (52.6%) of them remained in Category 3. Four students (21.1%) changed to a more favorable Category 2 and five (26.3%) changed to less favorable categories.

For Question #3

Two students 2.2% began in Category 1. One of the students remained in Category 1 and one student changed to Category 2.

Fifty four students began in Category 2 and forty (74.1%) remained in Category 2. Of the fourteen students who changed from Category 2 to other categories in the post-test, all of them changed to less favorable categories.

Twenty one students (22.6%) began in Category 3. Twelve of the twenty one (57.1%) students remained in the same category for the post-test. Eight students (38.1%) changed to Category 2, a more favorable category. One of the students changed to Category 4, a less favorable category.

See Table 4-1 for a summary of the tracking of the students given in the paragraphs above.

Table 4-1 Categories and Results – Version 2

Pre Category	# Same % Same	# Better % Better	# Worse % Worse
Q #1 Cat 1 Total # 5/93 Pre: 5.4%	3/5 60%	--- 0%	2/5 40%
Cat 2 36/93 Pre: 38.7%	27/36 75%	1/36 2.8%	8/36 22.2%
Cat 3 23/93 Pre: 24.7%	12/23 52%	6/23 26%	5/23 21.7%
Cat 4: 20/93 Pre: 21.5%	7/20 35%	10/20 50%	3/20 15%
Q#2 Cat 1 3/93 Pre: 3.2%	2/3 66.7%	0 0%	1/3 33.3%
Cat 2 57/93 Pre: 61.3%	43/57 75.4%	3/57 3.2%	11/57 19.3%
Cat 3 19/93 Pre: 20.4%	10/19 52.6%	4/19 21.1%	5/19 26.3%

Pre Category	**# Same % Same**	**# Better % Better**	**# Worse % Worse**
Q#3 Cat 1 2/93 Pre: 2.2%	1/2 50%	0/2 0%	1/2 50%
Cat 2 54/93 Pre 58.1%	40/54 74.1%	0/54 0%	14/54 25.9%
Cat 3 21/93 Pre: 22.6%	12/21 57.1%	8/21 38.1%	1/21 11.1%
Totals	Same 157/240 65.4%	Better 32/240 13.3%	Worse 51/240 21.3%

As mentioned earlier, the responses of the students were tracked from pre to post so we can find the answers provided by individual students for question #s 1, 2, and 3 from weeks one, two and three respectively.

We can see that the number of students in Category 1 was consistently very low. The number of students in Category 2 was quite uniformly higher than the number of students found in the other categories. The number of students and the percentage of students that did either better or worse on the post-tests were quite uniformly low. We can see from the above data that the results were quite stable for the different categories.

The results we obtain from the **graphs** of the data imply that there is no real change from pre to post. However, from the graphs, we do not know what individual students are doing (as mentioned earlier). Here, we obtain generally the same results, but we are tracking individual students. Therefore, we can determine whether or not students are trading places and we see they are not just trading places.

It is interesting to look further at the students who are in a certain category on the pre and then either stay the same, improve, or get worse on the post-test. The number of students who stay the same from the pre-test to the post-test significantly outweigh the students who improve or the students who get worse from Categories 1, 2, 3, and (Category 4 from question #2). We see that 157 students remained the same, 32 improved, and 51 got worse. It should be noted that students in Category 1 for the pre could not improve, but students in Category 2 or below could improve. It is also interesting to observe that approximately 75% of the students in Category 2 remained the same for Questions one, two and three.

Analysis of the data in Table 4-1 in terms of whether the student population changes or does not change categories from pre-test to post-test reveals that there is not a significant change in student descriptions of gravitational force. This is in agreement with the conclusions drawn from the Wilcoxon matched-pairs signed-ranks statistical tests.

The previous data support the general idea, illustrated by the earlier graphs and statistics, that there was not a large amount of movement from category to category, as indicated by the responses to the pre and post questions. That is, there was not a significant amount of change, on the part of the students, from pre to post responses in answering the questions on gravitational force.

At least two patterns observed in the earlier graphs are of interest. The first pattern is that there are almost no responses that are ideal on either the pre-test or post-test (See the graph in Figure 4-3 and Category 1 (Gravity interaction) in Table 3-1 or Table 3-2). The second pattern is that the largest numbers of responses occur in Category 2 (gravitational force or weight). While the Category 2 responses are not ideal, they are certainly better than the responses in Categories 3-6. Students were asked to describe the forces in a particular setting. Category 2 student responses included "gravitational force" and "weight of object." These might be considered reasonable responses, yet there are some caveats. The phrase "gravitational force" does tell what the force is called, but it is left to the reader to tell if the writer is thinking about a gravitational attraction between two objects. A student giving "weight of an object" or "force of gravity" as an answer might be thinking about an interaction between two objects, such as the earth and a person, or they might be thinking of "weight" or "force of gravity" as "an entity which can be possessed, transferred, and dissipated…)" rather than an interaction. (Chi 2008)

Results for Newton's Second Law Problems

The second content domain studied was related to Newton's Second Law. Students were asked in the pre-post questions to express Newton's 2nd law in equation form for each of the same three laboratory situations as were used for the gravitational force questions.

Scoring

The Newton's second law problems were scored either correct or not correct.

Week 1 Results for Newton's 2nd Law

The same situation that was used in week 1 for gravitational forces was used as the basis for the questions about Newton's second law. An accelerating, frictionless cart on a table is being pulled by a light cord that extends over a pulley and then down to object A (mass M). The students were to write two equations, one about the forces acting on the cart, and one about the forces acting on object A. The two equations the students produced were evaluated separately. The results for their equations related to the cart and object A are shown in Figure 4-4 and discussed below.

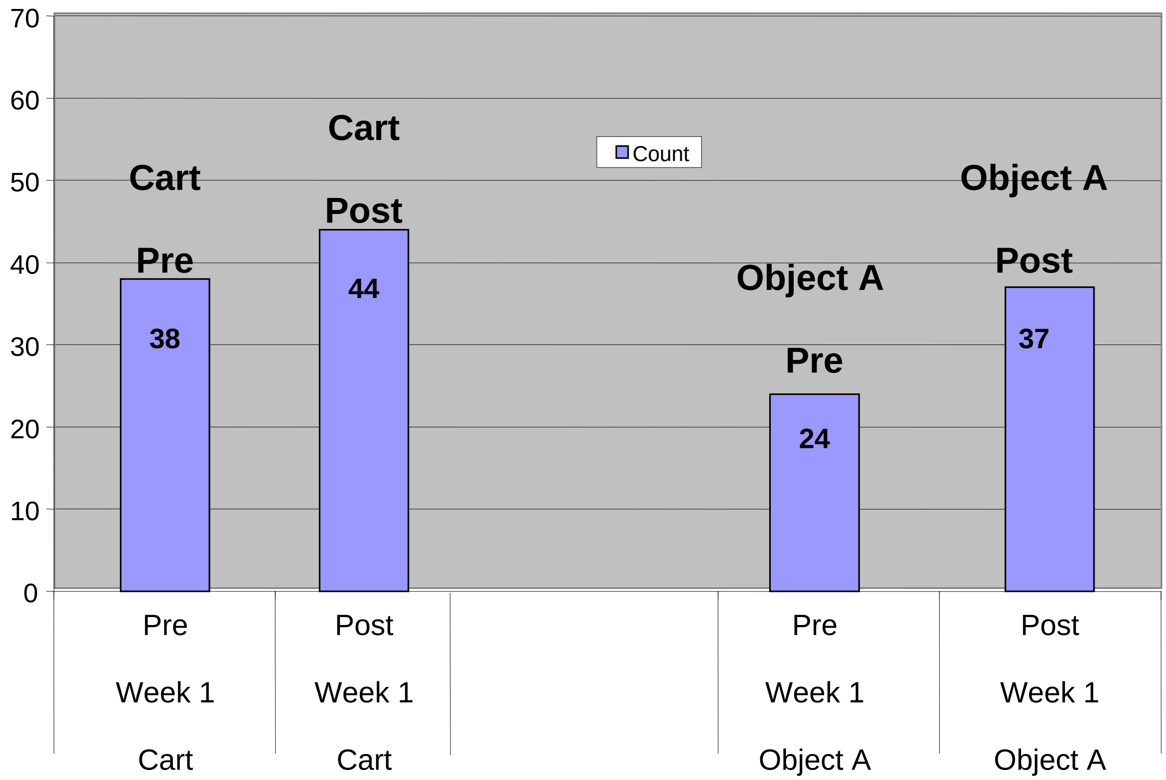
The difference between pre-test and post-test results for the 2nd Law question about the cart is statistically significant as indicated by a paired t-test ($p = 0.04$). However, the effect size is $d = 0.217$ which is considered small. That is, the students' ability to use Newton's 2nd law to write an equation showing the sum of forces acting on a cart in the "x" direction improved a small amount between the pre-test and post-test during Week 1.

Similarly, the difference between pre-test and post-test responses for the 2nd Law question about object A is statistically significant ($p = 0.015$), $N = 92$. The effect size is $d = 0.259$, which is considered small. There was a small improvement in students' ability to correctly use Newton's 2nd law in writing an expression for the sum of forces (in this case for object A).

In addition to the statistical findings, an important pattern is evident in Figure 4-4. The overall level of correct responses were low for both post-test questions, 44 out of 92

(48%) and 37 out of 92 (40%) correct respectively. This frequency of correct responses is too low to be considered acceptable, even given the slight improvements.

Figure 4-4 Newton's 2nd Law of Motion
Number of Students With Correct Answers for Cart & Object A in Week 1 (N = 92)

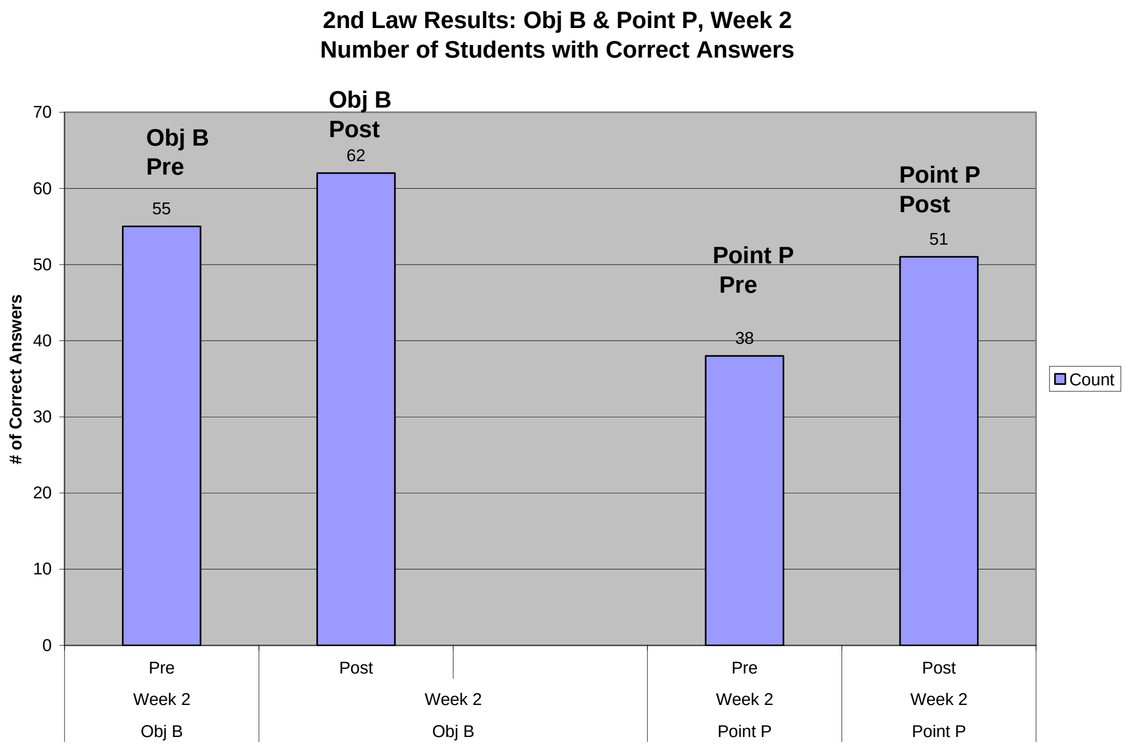


Week 2 Results for Newton's 2nd Law

The same situation that was used in week 1 for gravitational forces was used as the basis for the questions about Newton's second law. A central object B is suspended halfway between two pulleys by a light string. In week 2, the graph in Figure 4-5 shows the difference between pre-test and post-test results for object "B" being acted upon by forces.

The difference between pre-test and post-test results is not statistically significant. A paired t-test provides the result: ($p = 0.179$). Thus, the data tells us that the students' ability to use Newton's 2^{nd} law to write an equation showing the sum of the forces, in this case the sum of the forces on object B, did not improve. The difference between pre-test and post-test responses for point P is statistically significant ($p = 0.015$), $N = 92$ and the effect size is: ($d = 0.257$), which is also small. Here, we also see a small improvement in students' ability to correctly use Newton's 2^{nd} law in writing an expression for the sum of forces (in this case for the forces on point P). The pattern of responses for these post-test questions is somewhat better, with 62 out of 92 (67%) of the students responding correctly to the first question and 51 out of 92 (55%) responding correctly on the second question. That said, the numbers of the students responding correctly is still less than what would be considered acceptable.

Figure 4-5 Newton's 2nd Law of Motion
Number of Students With Correct Answers for
Object B & Point P in Week 2 (N = 92)



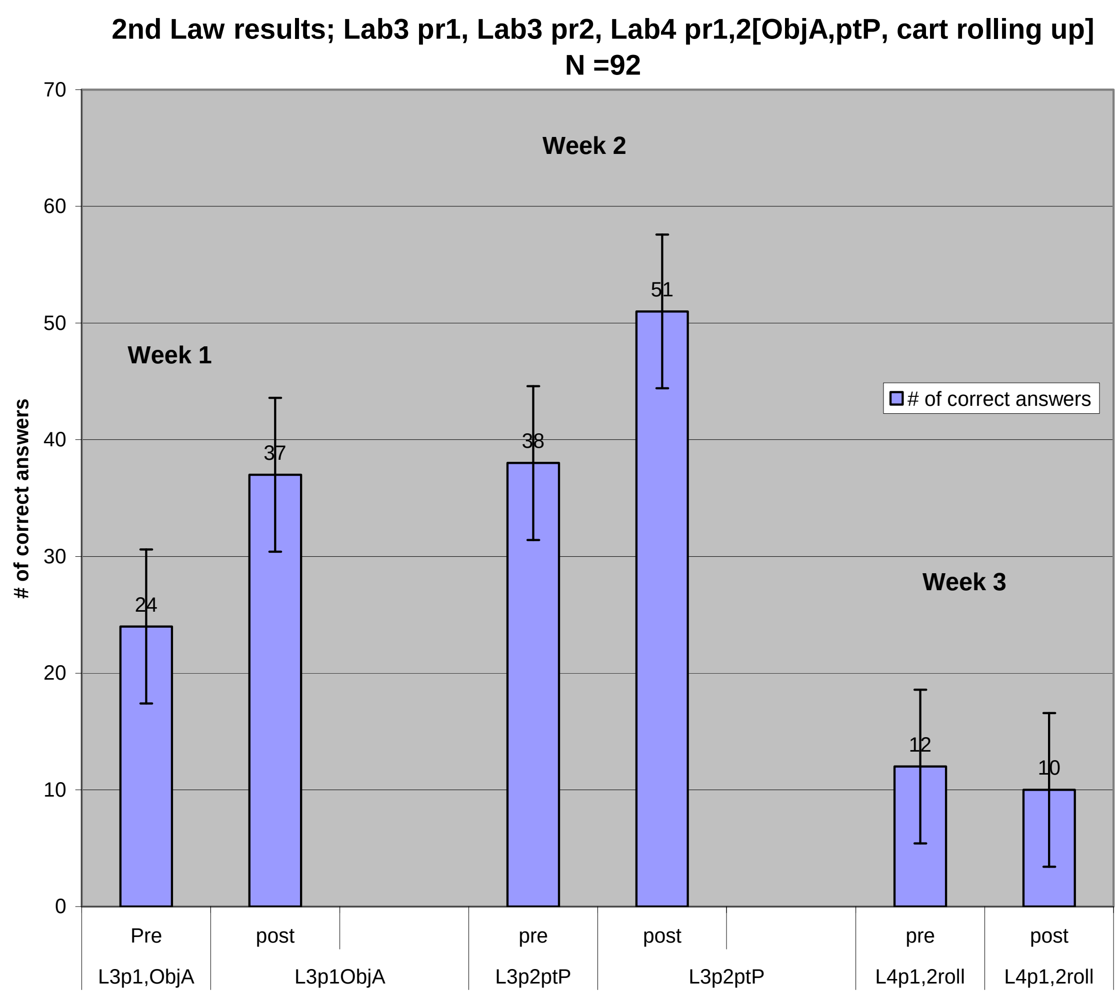
Week 3 Results for Newton's 2nd Law

Figure 4-6 shows the 3rd week results for a cart rolling up an incline.

This difference between pre and post is also not statistically significant as can be seen from the graph and from a paired t-test. We find: ($p = 0.530$). Again, the data indicates that the students' ability to use Newton's 2nd law to write an equation showing the sum of the forces, in this case forces on a cart rolling up an incline, did not improve.

In addition, the small number of correct answers on the post-test (10) was surprising when compared to the frequency of correct responses on post-test questions in week 1 and week 2. Only a very small percentage of students were successful in showing the sum of the forces using Newton's 2nd law for a cart rolling up an incline. This suggests that the nature of this problem is somehow very different for the students. In fact, given that the percentages of correct responses on the post-tests varies from a low of 11% (See Figure 4-6; 10/92 = 11%) to a high of 67%, (See Figure 4-5; 62/92 = 67%) suggests that the students ability to apply Newton's 2nd Law varies depending upon specific features of the problem.

Figure 4-6 Newton's 2nd Law of Motion
Number of Students With Correct Answers for Weeks 1, 2, and 3 (N = 92)



Overall Summary of Results

Changes, if any, in Skill Levels Related to Qualitative Analysis in Problem Solving (See Table 4-2 below)

Table 4-2 provides a summary of the results for changes, if any, in response to questions about gravitational force and Newton's 2nd law of motion. A change that shows improvement and is statistically significant is meant to indicate an increase in skill levels related to qualitative analysis in problem solving.

None of the results considering gravitational force showed statistically significant improvement and very few students responded at the highest level of correctness to the questions about gravitational force. The qualitative aspects of representing Newton's 2nd law of motion indicated some statistically significant improvement from pre to post questions for three of the five questions, but where there was statistically significant improvement the effect sizes were small. The inconsistency in statistically significant changes across the questions makes it difficult to claim improvement in the students' application of Newton's 2nd law. When this finding is coupled with the low level of correct responses on the post-test on all questions, the most defensible claim would be that the instruction related to Newton's 2nd law did not function as expected.

The following list of items that students did not do correctly provides examples of factors that caused the responses dealing with Newton's 2nd law to be of lower quality than was expected.

1. Students did not indentify the forces they were summing.
2. When the sum of quantities was equal to zero, they did not indicate that was the case.

3. Students indicated the sum of forces was zero, but did not identify the forces they were summing.

4. Students indicated the net sum of forces was zero, but did not show directly how the forces provided a zero resultant.

5. Students indicated that the difference between two forces was an acceleration rather than another force.

Table 4-2 provides statistical results for the questions about gravitational force and Newton’s second law of motion. (The results in Table 4-2 have been provided earlier in the dissertation. They are repeated here for handy reference.)

Table 4-2 Statistical Results for Questions About Gravitational Force and Newton’s Second Law of Motion

Note: (NSD) means no statistically significant difference. (SD) means statistically significant difference.

Gravity	**Newton’s 2nd Law of Motion**	
Week I - NSD Cart & Obj A Questions Pre-post Wk 1, Wilcoxon (p = 0.678, n = 93)	Week I – SD Cart Question Pre-post Wk 1 Paired t-test (p = 0.04) (d = 0.217, n = 92)	Week I – SD Object A Question Pre-post Wk 1 Paired t-test (p = 0.015) (d = .259, n = 92)

Gravity	Newton's 2nd Law of Motion	
Week II, - NSD Obj B & ptP Question Pre-post Wk 2 Wilcoxon (p = 0.378, n = 93) gravity	Week II – NSD Object B Question Pre-post Wk 2 Paired t-test (p = 0.179, n = 93) 2nd law	Week II – SD Point P Question Pre-post Wk 2 Paired t-test (p = 0.015, d = .257, n = 92) 2nd law
Week III, - NSD Cart rolling up Question Pre-post Wk 3 Wilcoxon (p = 0.451, n = 93)	Week III –NSD Cart rolling up Question Pre-post Wk 3, Paired t-test (p = 0.530, n = 92)	In week III there was only one question on Newton's second law (See "box" to the left)

Information Regarding Students in the Lab Setting and Aspects of the Lab Experience

From observations performed of the TAs, discussions with the TAs, and with the mentor TAs, the following conclusions were drawn. Some of the aspects of the labs were quite uniform as can be seen by the following list.

1. All TAs and students used the same lab manuals and did the same lab problems that were involved in this study.
2. The lab sessions all had 12 to 16 students.
3. The students all worked in groups in the lab. Generally there were three students per group, sometime four students.
4. The group members were selected by the TA.

5. All students were required to do method questions (warm-up questions) before the beginning of the lab sessions.
6. All students were required to complete the laboratory investigations that would verify or challenge their initial problem solutions
7. All students were required to write and hand in lab reports.
8. Students attended lectures and participated in the weekly discussion sessions.

TA Teaching Practices

As part of the descriptive nature of this research, we are interested in what the TAs do when teaching the labs. The TAs are given a number of guidelines concerning the nature of the instruction they provide. These guidelines have come from the work done by Heller and Heller et al. and are described in the Instructor's Handbook: A Guide for TAs (Heller et al. 2005)

Table 4-3 identifies the categories for lab teaching guidelines followed by a graph showing the percentages of TAs following the different teaching guidelines.

Table 4-3 Categories for Laboratory Teaching Guidelines

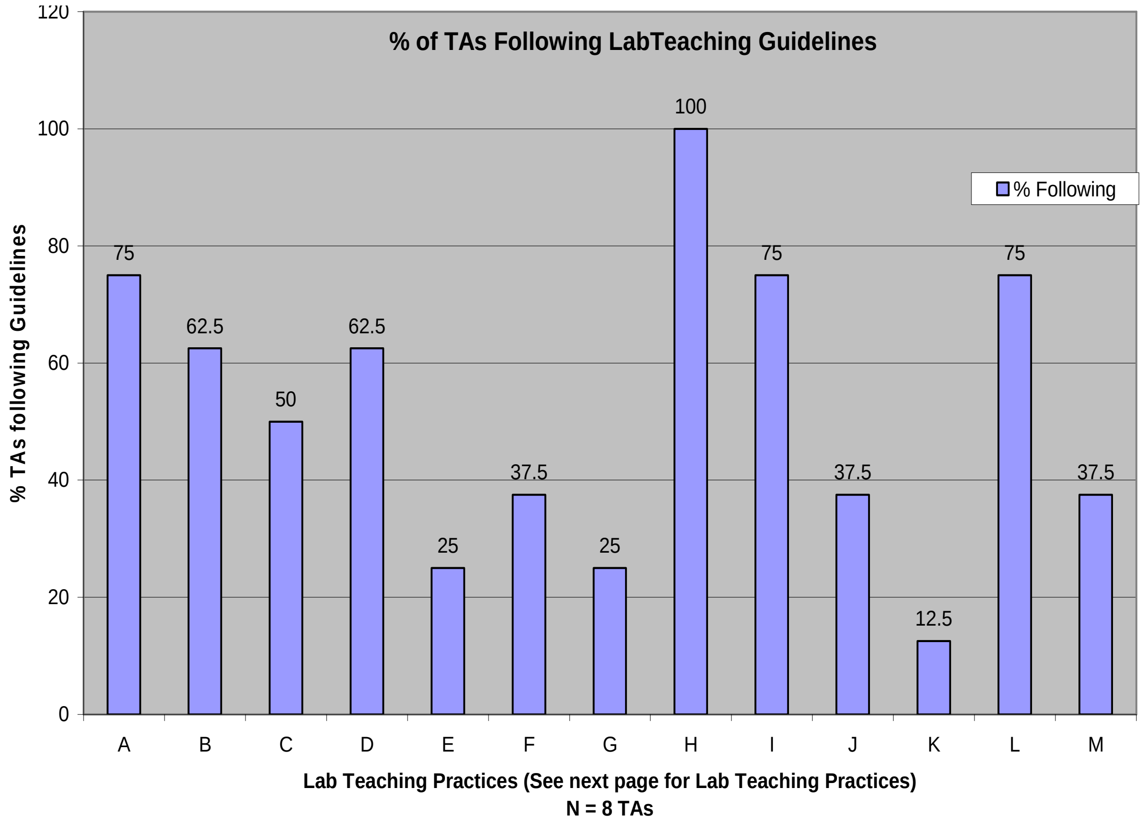
A. Students put Method Questions on board (under direction of the TA)
B. Leading Class Discussion
C. TA does not give a lecture about the lab
D. TA asks questions while working with whole class
E. Method Question answers not confirmed by TA at START of lab session

Table 4-3 Categories for Laboratory Teaching Guidelines

F. Time for class discussion at start of lab
G. Students start working with equipment a short time after lab session starts
H. TA coaches groups
I. TA interacts with all groups during each 10 minute interval
J. Students put lab results and/or method question answers on board
K. TA leads class discussion near end of lab session
L. TA does not give a lecture on lab topics near end of lab session
M. TA asks questions of individuals during whole class discussion

There were some variations in how closely the TAs followed the teaching guidelines. However, the overall structure of the lab situations was the same. Of course, students attended lectures and participated in the weekly discussion sessions so they also had those experiences in common.

Figure 4-7 Percent of TAs Following Lab Teaching Guidelines



As pointed out earlier, there is a definite structure to the introductory physics classes including lectures, group problem solving discussion sessions, and lab sessions. Even though the lab sessions had different TAs, there were many features of the labs that were constant for all lab sessions. On the other hand, there were differences such as TAs who were native English speakers and, in our sample, an equal number of non-native speakers. Figure 4-7 indicates that there were differences in the lab teaching guidelines followed by the TAs. The sample size in this study was not large enough to compare the results for factors such as native vs non-native English speakers or comparision of results according to the differences in following of guidelines. These factors should be studied in future research.

Chapter 5 Conclusions and Implications

Introductory Physics Labs at the University of Minnesota

This is a descriptive study of introductory physics labs at the University of Minnesota. These labs are part of what is traditionally the first physics course taken at the University of Minnesota by students planning to study in the fields of science and engineering.

As mentioned earlier, these labs are rather unique. They are not the kind traditionally found in introductory physics labs at universities and colleges. They are cooperative problem solving labs (CPS labs). The students are asked to answer warm-up questions directly related to the problems they will work on in the lab sessions. The warm-up questions are answered individually, outside of the lab session. Students are free to share ideas with other students, but there is no formal arrangement to have the students work in groups before the lab session. These warm-up questions are submitted to the TA a day before the lab session. The warm-up questions are intended to raise questions and point the students in the right direction to solve the lab problem(s). The student responses provided in the warm-up questions also provide the TA with some understanding of the progress made by the students and the help they might need. In the lab session, the students collaborate, in groups of three, to see if they have solved the lab problem(s) correctly, so they can make a prediction that will answer the question posed by the lab problem. Students are to decide which measurements to make, how to make them, and check their results using computers and other lab equipment.

Qualitative Analysis Skills

Qualitative analysis skills are an important part of the problem solving process. Since the problem solving process is important in these labs and qualitative analysis skills are an important component of problem solving as discussed in chapter 2, (Larkin 1979) (Woods 1987) (Reif and Heller 1982) it was important to attempt measurement of qualitative analysis skill levels, and the changes in those levels, as a key part of the study. This leads to the research question which is presented again.

The Research Question

> **In what ways, if at all, do students' qualitative analysis skill levels change, in the domain of Newton's 2nd law and in the domain of gravitational force, from pre-test to post-test during a two hour lab period and as measured during three successive lab periods each of the lab periods being one week apart? For the purposes of this study the qualitative analysis of a lab problem includes the physics and mathematical representation of a problem.**

This is a study about using labs to check the validity of "on-paper" problem solutions using a cognitive apprenticeship model (Farnham-Diggory 1994). Cooperative groups (Johnson et al. 1991) (Johnson et al. 1998) were used as part of the cognitive apprenticeship model.

The lab sessions begin with the TA asking students from different groups to write responses to some of the warm-up questions on the board. There is a brief class discussion, for 10 or 15 minutes lead by the TA, about some of the warm-up questions. (The TAs receive the warm-up question responses the day before the lab so they are able to see where students might have difficulties.) After the brief discussion, students work in their groups to validate their problem solutions. To use the lab equipment, the students, working as a group, need to develop a plan to perform the necessary measurements that will allow them to confirm the results they obtained in solving the lab problem.

In this setting, the students are participants in peer coaching and coaching by the TAs. The cooperative groups function to assist the students in their quests to solve the problems and to validate their answers using computers and other lab equipment. During the last 15 minutes, the groups write results on the board and the TA leads a brief discussion about key ideas in the lab problems. The goal of the labs is to increase students' skills in the problem solving process and to improve their understanding of physics principles.

Gravity: Starting Points, Lack of Differences Between Pre and Post, and Patterns in Results

The pre-test results indicated that there were very few scores in the top gravitational category. For example results for the pre-tests in weeks one, two, and three indicated that only 5 students out of 92, 3 students out of 92, and 2 students out of 92 respectively, provided responses in the best (most correct) category on the pre-tests.

The differences between the pre-tests and post-tests were not statistically significant. There was no discernable change in the students' qualitative analysis skills from pre-test to post-test in the domain of gravitational force. (See Figures Figure 4-1, Figure 4-2 and Figure 4-3 in chapter 4 or Table 4-2 in chapter 4.)

We can see from data in chapter 4 that there were opportunities for change. In week one, 59% of the responses about gravitational force did not change. In week two, 67% of the responses did not change and in week three, 67% of the gravitational responses did not change. We are left with the question "why such small change?" when the opportunity for change existed?

A reason for no change from pre-test to post-test might be found in students' previous ideas about gravity. (Redish 2003) Generally students have had ideas about gravity for a long time. Ideas that have been held for a long time are often very difficult to change. "Common naïve conceptions can be strikingly robust." (Redish 2003, 40) There are many reasons why long held ideas don't easily change. Students may have had many experiences in which their initial ideas have been necessary and sufficient to generate useful, positive results. Ideas that seem to successfully provide explanations over a long time frame are not easily abandoned. Often, students have initial ideas that are congruent with and supported by the common language of their lives.

Everyday language can influence student thinking. For example, the phrase "may the force be with you", as used in popular film, provides the sense that force might be an entity which can be possessed or transferred to someone else. (Chi 2008)

The Category 2 responses suggest the possibility that there is a fundamental error being made. The error may be, as mentioned above, that the students are considering the force of gravity as an *entity*. In looking for student responses that talk about gravitational force as an interaction between two objects, we might ask if the concept of interaction between objects is often emphasized by physics instructors or if it is more commonly not mentioned. This could influence the way students think about gravitational interaction.

Other improvements would be needed to reduce the number of Category 3 – 6 responses and raise the number of ideal responses.

As mentioned in chapter 2, Maloney cites the work of Terry and Jones who comment about students:

> "This suggests that they do not have an understanding of the concept of force and interactions between two objects or that the forces involved in the interaction can be described by the third law. There was no indication that pupils generally think of an interaction in terms of an equal and opposite pair of forces. Yet such an understanding is central to an understanding of the overall concept of force." (Terry and Jones 1986)

Tougher is in agreement with this discussion. He tells us: “The physicist thinks of forces as actions – more specifically as interactions.” (Tougher 1991, 46)

Newton’s 2nd law: Starting Points and Differences Between Pre and Post

Chapter 4 shows (See Figures 4-4, 4-5, and 4-6.) that a relatively small number of students provided correct answers on the pre tests that asked about the use of Newton’s 2nd law. In week one, 38 students on the pre test out of 92 students responded correctly to one of the 2nd law questions and 24 students out of 92 on the pre-test responded correctly to another 2nd law question. In week two, 55 students out of 92 responded correctly on the pre-test for one of the questions and 38 out of 92 responded correctly on the pre-test for another question. In week three, only 12 students out of 92 on the pre-test responded correctly to the question about the 2nd law. (See the summary in Table 5-1 that provides the number and percentage of students providing correct responses on the pre-tests for Newton’s 2nd law questions.)

Table 5-1 Summary of Number of Students Out of 92 Responding Correctly on the Pre-tests for Newton’s 2nd Law Questions

Number of students correct out of 92 on the pre	Object	Week
38/92 41%	Cart	Week 1
24/92 26%	Object A	Week 1
55/92 60%	Object B	Week 2
38/92 41%	Point P	Week 2
12/92 13%	Cart rolling up	Week 3

The results for three of the five Newton's 2nd law Pre-Post Questions indicated a statistically significant increase in skill level from pre-test to post-test. (Question 1, $p = 0.04$; Question 2, $p = 0.015$; Question 4, $p = 0.015$). While the results were statistically significant, the effect sizes were small and the results for two of the five problems were not statistically significant. In general, the results suggest that the labs had only a limited effect in the domain of Newton's 2nd law. The small number of students whose ideas were correct at the beginning suggests there was plenty of room for change.

Furthermore, we can see from the graphs dealing with Newton's 2nd law that the number of students responding with correct scores was not large, even for questions that had the highest number of correct answers. Only 62 out of 92 students provided correct post answers for object B in week two, and only 51 students out of 92 on the post-test provided correct answers for point P in week two. The number of correct responses for the other pre-post questions dealing with Newton's second law were all lower than those mentioned above.

Conclusions and Implications

We cannot say that we had success in finding positive gain in the description of gravitational force and we found that very little gain in the domain of using Newton's 2nd law to write equations representing the sum of forces.

We do however have a sense of where the students were midway through the semester in terms of their descriptions of gravitational force and their use of Newton's 2nd law to write equations representing the sum of forces. Both of these are related to the quantitative analysis aspects of problem solving.

Conclusions and Implications Regarding Gravity

The results of this study were surprising. The grounding of the laboratory- based instruction design in the cooperative learning, cognitive apprenticeship and problem solving literature predicted that the results would be substantially better. As mentioned in chapter 2, Redish suggests: "The laboratory is the traditional instructional environment that is, in principle, best set up for independent active-engagement learning in line with our cognitive model of learning." (Redish 2003, 162)

The cooperative problem solving (CPS) design (at the University of Minnesota) uses a cognitive apprenticeship model in the labs and throughout the course. Brown, Collins, and Duguid, as well as Farnham-Diggory, present and discuss this cognitive apprenticeship model. (Brown, Collins, and Duguid,1989) and (Farnham-Diggory, 1994). Cooperative learning ideas developed from discussions held by Heller, Hollabaugh, Keith and Anderson with Johnson, Johnson and Smith developed the CPS design at the University of Minnesota. At the University of Minnesota, when cooperative learning, cognitive apprenticeship and a problem solving strategy have been used in discussion sessions and lab sessions, in conjunction with the modeling of a problem solving strategy in lectures, the results have been a significant increase pre-test to post-test on the Force Concept Inventory (FCI). (PER Group University of Minnesota) It should be noted that the pre-test to post-test FCI scores referred to here covered a whole semester. (The FCI was administered at the beginning and end of one complete semester.) In addition, other studies have shown student success when the outcomes were measured by the widely used Force Concept Inventory. The result of the unexpected outcome in this study is the obligation to consider why the results were so poor.

One reason for the unexpected results could be the huge difference in time span. The example of the FCI given above, from the University of Minnesota, was over a whole semester. The data we are talking about for this study considered data from two-hour lab sessions. Considering the short time span in this study, one might expect to find a "no change" result.

Other reasons for the lack of difference between pre-test and post-test responses include the following: The instruction was not delivered as rigorously as is needed. Another possibility is that in spite of the well designed instruction, the effects of the instruction could not replace or explain to the students the flaws in students' deeply held conceptions. Another possibility is that the students continued to simply view physics problem solving as symbol manipulation, and thus "see" no need to actually understand the concepts that are involved.

Each of the above reasons suggests the need for additional research.

Considering the gravitational results, we observe that more responses were in Category 2, both for the pre-tests and the post-tests, than in any other category. Students were asked to describe the forces in a particular setting. Category 2 student responses included "gravitational force" and "weight of object." In some ways, these are acceptable responses, yet they do not identify exactly what the student is thinking. The phrase "gravitational force" does identify what the force is called, but it remains for the reader to discover if the writer is thinking about a gravitational attraction between two objects. A student providing "weight of an object" or "force of gravity" as an answer might be thinking about an interaction between two objects, such as the earth and a person, or as mentioned in chapter 4, they might be thinking of "weight" or "force of gravity" as "an *entity* which can be possessed, transferred, and dissipated…" (rather than an interaction) (Chi 2008, 71)

The small number of Category 1 responses in the domain of gravitation, for either pre-test or post-test, was not an encouraging result because responses in this category would be those indicating that students understood the gravitational force as an interaction between two objects. This is a very important Newtonian concept that students should understand.

We can ask: "What is taking place in the lab that does not seem to foster student answers (or understanding) about this Newtonian concept?" As mentioned in Chapter 2, Redish suggests: "The laboratory is the traditional instructional environment that is, in principle, best set up for independent active-engagement learning in line with our cognitive model of learning." (Redish 2003, 162) Alternatively, it might be that there are so many things going on in lab that students have difficulty focusing on concepts such as gravity and Newton's 2nd law. For example, in lab students are supposed to be dealing with and understanding the lab problems that are assigned. They have to devise a measurement plan and carry out that plan so they can verify the solutions to the lab problems. Gaining expertise in problem solving is another of the objectives of the lab. Students are also supposed to gain enough information and understanding so that they can write up a lab report. The labs at the University of Minnesota are not traditional labs, yet some of the factors observed by Redish could be a factor in Minnesota labs. From observation of traditional laboratories, as mentioned in chapter 2, he tells us: "Our video tapes show students spending most of the period trying to read the manual and figure out what it wants them to do. The students make little or no attempt to synthesize in order to get an overview of what the point of the lab is. Almost all of the discussion concentrates on the concrete questions of how to configure, run, and get information from the apparatus. There is little or no discussion of the purpose of the measurement, how it will be used, the physics to be extracted, or the limits of the measurements." (Redish 2003, 162).

There are also other factors at work. It could be that the treatment, i.e. the lab session, is not strong enough to uproot students deeply and firmly held ideas until the other parts of the course come into play. Other parts of the course include discussion sessions (which involve cooperative group problem solving), lectures, individual efforts spent on problem solving, studying with classmates, and time spent working with TAs in the TA student help room. Perhaps these other factors are very important in bringing about change in understanding. Perhaps the time spent in lab is too short and the distractions too many to allow significant change during the lab period alone.

Finding very few responses in Category 1 (gravitational force as an interaction between two objects that involves a mutual attraction between the objects) tells us that the way of thinking indicated by that category was not a common way of thinking by the students in our study. This suggests that the people involved in physics instruction should consider a different approach to the teaching of the conceptual understanding of gravitational force. The teaching approach should encourage the adoption of the conceptual understanding described by Category 1. The first step might be bringing to the attention of TAs and professors the apparent dearth, on the part of the students, of understanding/acceptance of the conception of gravitational force described as an interaction between two objects. These objects have mass, and this interaction involves a mutual attraction between the two objects. The idea that students might consider gravity an entity also leaves open the question of how the instructional process should address such a student held perspective.

Implications Because of Nature of Students' Responses In the Domain of Gravitation

As suggested above, some changes in teaching practices and/or emphasis on students' understanding and perspective of gravitational force might be worthwhile. For example, when talking about vectors that represent gravitational force, instructors might verbalize as follows: "interaction between two objects that have mass is responsible for the gravitational force of attraction between two objects." Of course an instructor would have to discuss this statement with the class it would not be enough to just make one statement and move on. This type of verbalization, on the part of the instructor, in addition to the drawing of a force vector and labeling it "F_g" along with discussion about the meaning would be appropriate. Asking students to make note, in diagrams when solving problems, of the meaning of F_g could also be a useful approach. Some of the qualitative aspects of problem solving are commonly not shown when the solution to a physics problem is presented. This is often true when an instructor solves a problem in class. (Foster 2000, 42) This is supported by Leonard et al. who state: "When modeling problem solving for students, although we are usually careful to state verbally the principle or concept being applied to solve a problem, we often only *write down* the equations by which the principle is instantiated. Students, therefore, observe that it is the manipulation of equations that leads to solutions; their perception is that principles are abstractions that bear little relevance to obtaining answers to problems." (Leonard et al. 1996, 1496) Of course, it might take more than this. It might take extensive effort to change students' conceptions. Activities that directly challenge student held conceptions can be important.. Also very important can be activities that demonstrate that the physicists' view is better than some student conceptions. (Redish 2003)

Possible Explanations for Students' Responses In the Domain of Newton's 2nd Law of Motion

One possible explanation for the pattern of results across the five questions on Newton's 2nd law is that they are of variable difficulty. This idea is supported by the large drop in the number of correct responses, both pre-test and post-test, from week two to week three. The fifth problem seems to be much more difficult than the other four. Research is needed into the reasons that problems from the same domain, which seem to require the same knowledge to solve, produce incorrect responses.

To increase student success in a problem such as this, that has a cart moving up an incline, one might start with slightly different problems. For example: push a cart on a horizontal surface that **has** friction. Let the cart move on its own on the surface. Ask students to write Newton's 2nd law for the cart moving on the horizontal surface. [Write the x-coordinate component of Newton's 2nd law ($\Sigma F_{x\,=}\, ma_x$, where"Σ" means the sum of the forces) for the cart rolling on the friction surface.]

The labs at the University of Minnesota are considered cooperative problem solving labs (CPS labs). In solving problems, novices tend to look for an equation. "Experts classify problems by what physics principles are most relevant, such as energy vs. force analysis. Novices classify them by surface structure and superficial associations (e.g., it's an inclined plane), ..." (Redish 2003, 122) Students might be in the habit of looking for equations rather than understanding basic principles such as Newton's 2nd law of motion. This could mean they have not paid attention to complete statements of Newton's 2nd law including the sum of forces. This lack of complete understanding of the 2nd Law might cause them to write abbreviated and or incorrect responses when asked to write representations of Newton's 2nd law of motion. In light of these comments, instructors might be motivated to encourage more complete understanding by requiring a well defined problem solving strategy and awarding credit on quizzes and tests to students who follow such a strategy. For a description of such a strategy see Heller or Redish (Heller 2006, 2-3) (Redish 2003, 159).

Students may be having more or less difficulty with problems for reasons we do not understand.

Discussion of Factors Influencing This Study

Many factors may have influenced the results of this study. One major factor may be the TAs. The data in chapter 4 indicate that the TAs did not rigorously follow the guidelines for teaching the labs.

Another factor may be the differences in English language capabilities of the TAs. Those differences might influence the student results. There were eight different TAs teaching the eight lab sessions. Half of the TAs were non-native English language speakers and the other half were native English language speakers. It is possible that there are differences in the ways that the TAs with different language abilities were able to assist the students.

The incomplete use of the suggested teaching protocol by the TAs, and in some cases language abilities, may have caused students to have different experiences in the lab session. This may mean that even when carefully designed lab activities, that combine laboratory verifications of on-paper problem solutions with a cognitive apprenticeship approach and cooperative group interactions, the TAs may have a large impact. An examination of the differences in TA interactions with the students and the possible effects of that on the students' performance is beyond the scope of this study, but can and should be examined using the available data.

Second, there were three different professors teaching the large lecture sections. Students from two professors were chosen at random to be in the study. The difference between what the two professors did during their lectures may have been a factor. Unfortunately, that question cannot be examined properly with the current data. Another set of data in this area will be needed. Such a study would require obtaining elaborated descriptions of the teaching by different professors.

A third factor may be related to the fact that students had different sequences of lab and lecture. Some students had lectures before the lab sessions and some had lectures after the lab sessions, because of the days on which they had labs. This meant that some students encountered ideas from lecture before the lab session and other students encountered those ideas for the first time in the lab. The effects of this matter are unknown, but could be examined in other studies.

Time Span for Learning

Two hours is a relatively short time span to change the concepts held by students. There are many factors that go into the learning process, in addition to the lab sessions. Students worked on warm-up questions before the lab. They attended lectures and they worked independently on problem assignments. Some students worked with other students when solving physics problems. Some students received help from TAs and professors during office hours.

For more improvement, perhaps there are different ways in which the teaching learning process should be implemented.

The labs were based on the concept of having students solve problems and validate their initial problem solutions in the lab using computers and other lab equipment. The lab problems were designed so that a problem solving strategy would be useful in solving the problems. To validate the problem solutions in the lab, appropriate equipment was available and used by the students while working in their cooperative groups.

We saw some small effects on student improvement in the qualitative aspects of problem solving, but not the expected effects.

Measurements of Qualitative Analysis Skills

There are some questions one might encounter regarding conducting measurements of qualitative analysis skill levels. A first question might be: Is it possible to actually make measurements of qualitative analysis skill levels? Suppose the answer to this question is yes. Then we ask: Are we using the correct methods to measure qualitative analysis skill levels? Comments, discussion, and references earlier in this dissertation support the idea that the quantities measured in this study do provide information about qualitative analysis skill levels. The next question might be: Are our measuring techniques sensitive enough to detect statistically significant changes in skill levels? The results given in chapter 4 suggest that we have measured changes in skill levels in the domain of Newton's 2^{nd} law of motion, but in the domain of gravitational force no significant changes were detected.

No detection of significant changes does not mean the measuring techniques were at fault. The measurements that were performed did provide us information about the level of student understanding at that time in the physics course.

Asking instructors to place special emphasis on gravitation and Newton's 2^{nd} law when used in solving problems could provide the opportunity to investigate if understanding of these concepts changed due to a change in emphasis by instructors.

Considering opportunities for further investigation, one could perform a more detailed analyses of students' errors in the Categories 3 – 6 for gravitation and for the Newton's second law problems. They could be very useful as a basis for understanding more completely how the instruction could be improved.

Many other opportunities exist for improving student understanding of concepts in physics. For example, in the physics labs one could investigate student understanding of conservation of energy, kinetic energy, momentum, conservation of momentum, conservation of angular momentum, and many others.

Recommendations for Problem Solving Labs

All the suggestions given here are difficult and fundamentally challenge contextual constraints and "typical" practices.

- Provide intensive and sustained TA education, coaching and continuous assessment
    - Focus this instruction on those aspects of cognition, apprenticeship and cooperative learning that could be most critical and are least utilized.
- Stabilize the population of TAs that teach the labs. It takes a lot of education and experience to teach as prescribed by the program.
- Provide more coaching of individual students on each type of problem. This would require instruction on fewer topics.
- Provide more instruction on understanding "the details of the concepts" (e.g., the idea that gravitation involves an interaction between two objects).
- Develop problems, perhaps mini problems, that focus on ameliorating specific misconceptions and other student errors.

Research Opportunities

- Investigate the suggested recommendations.
    - Each investigation will require sustained research – design – evaluation – redesign – evaluation cycles using many small scale, in-depth studies that can be expanded to larger scale studies.
    - The smaller scale, in depth studies of a few students and TAs are essential to determining the specific strengths and weaknesses of the CPS approach and to suggest modifications in that approach, the problems and the TAs' education.

- The larger scale studies are needed to see if the modifications can be "scaled up" and to validate the effectiveness of CPS.

The five components of cooperative learning mentioned in chapter two could be useful in developing a research program to investigate learning in introductory physics labs.

It should be noted that the University of Minnesota Physics Department has a strong orientation program for new TAs. It includes a week of orientation on teaching the labs and a weekly seminar for the first year TAs. Selected experienced TAs serve as mentors for the new TAs during the first year. The mentors work with the faculty member(s) in charge of the program by helping with the orientation before school starts in the fall and in the weekly seminars. Mentor TAs also observe the new TAs teaching labs and provide feed-back and a chance to discuss items of interest and concern to the TAs and the mentors. The research mentioned above could well be found useful for improving the introductory labs in many schools including the strong program at the University of Minnesota.

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Appendix

Example of a Lab Problem and Method Questions

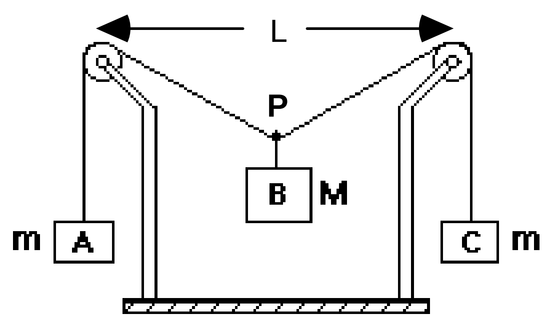
You have a summer job with a research group studying the ecology of a rain forest in South America. To avoid walking on the delicate rain forest floor, the team members walk along a rope walkway that the local inhabitants have strung from tree to tree through the forest canopy. Your supervisor is concerned about the maximum amount of equipment each team member should carry to safely walk from tree to tree. If the walkway sags too much, the team member could be in danger, not to mention possible damage to the rain forest floor. You are assigned to set the load standards.

Each end of the rope supporting the walkway goes over a branch and then is attached to a large weight hanging down. You need to determine how the sag of the walkway is related to the mass of a team member plus equipment when they are at the center of the walkway between two trees. To check your calculation, you decide to model the situation using the equipment shown below.

EQUIPMENT

The system consists of a central object, B, suspended halfway between two pulleys by a string. The whole system is in equilibrium. The picture below is similar to the situation with which you will work. The objects A and C, which have the same mass (m), allow you to determine the force exerted on the central object by the string.

You need to make some assumptions about what you can neglect. For this investigation, you will need a meter stick, two pulley clamps, three mass hangers and a mass set to vary the mass of objects.



PREDICTION

Predict the vertical displacement of the central object B in terms of quantities that you can directly control in the experiment. Use your equation to make a graph of the vertical displacement of object B as a function of its mass (M).

METHOD QUESTIONS

Read: Fishbane Chapter 4. Read carefully Section 4-6 and Example 4-12.

To solve this problem it is useful to have an organized problem-solving strategy such as the one outlined in the following questions. You should use a technique similar to that used in Problem 1 (where a more detailed set of Method Questions is provided) to solve this problem.

1. Draw a sketch similar to the one in the Equipment section. Draw vectors that represent the forces on objects A, B, C, and point P. Use trigonometry to show how the vertical displacement of object B is related to the horizontal distance between the two pulleys and the angle that the string between the two pulleys sags below the horizontal.
2. The "known" (measurable) quantities in this problem are L, m and M; the unknown quantity is the vertical displacement of object B.
3. Write down the acceleration for each object. Draw separate force diagrams for objects A, B, C and for point P (if you need help, see your text). Use Newton's third law to identify pairs of forces with equal magnitude. What assumptions are you making?
4. Which angles between your force vectors and your horizontal coordinate axis are the same as the angle between the strings and the horizontal?
5. For each force diagram, write Newton's second law along each coordinate axis.
6. Solve your equations to predict how the vertical displacement of object B depends on its mass (M), the mass (m) of objects A and C, and the horizontal distance between the two pulleys (L). Use this resulting equation to make a graph of how the vertical displacement changes as a function of the mass of object B.
7. From your resulting equation, analyze what is the limit of mass (M) of object B corresponding to the fixed mass (m) of object A and C. What will happen if $M>2m$?

EXPLORATION

Start with just the string suspended between the pulleys (no central object), so that the string looks horizontal. Attach a central object and observe how the string sags. Decide on the origin from which you will measure the vertical position of the object.

Try changing the mass of objects A and C (keep them equal for the measurements but you will want to explore the case where they are not equal).

Do the pulleys behave in a frictionless way for the entire range of weights you will use? How can you determine if the assumption of frictionless pulleys is a good one?

Add mass to the central object to decide what increments of mass will give a good range of values for the measurement. Decide how measurements you will need to make.

MEASUREMENT

Measure the vertical position of the central object as you increase its mass. Make a table and record your measurements with uncertainties.

ANALYSIS

Graph the *measured* vertical displacement of the central object as a function of its mass. On the same graph, plot the *predicted* vertical displacement.

Where do the two curves match? Are there places where the two curves start to diverge from one another? What does this tell you about the system?

What are the limitations on the accuracy of your measurements and analysis?

CONCLUSION

What will you report to your supervisor? How does the vertical displacement of an object suspended on a string between two pulleys depend on the mass of that object? Did your measurements of the vertical displacement of object B agree with your predictions? If not, why? State your result in the most general terms supported by your analysis.

What information would you need to apply your calculation to the walkway through the rain forest?

Estimate reasonable values for the information you need, and solve the problem for the walkway over the rain forest.

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