# COMPARING THE SCAFFOLDING PROVIDED BY PHYSICAL AND VIRTUAL MANIPULATIVES FOR STUDENTS' UNDERSTANDING OF SIMPLE MACHINES

by

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B.A., Drew University, 2006

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Physics
College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2010

# Abstract

Conventional wisdom has long advised that students' learning is best supported by interaction with physical manipulatives. Thus, in the physics laboratory, students typically spend their time conducting experiments with physical equipment. However, computer simulations offer a tempting alternative to traditional physical experiments. In a virtual experiment, using a computer simulation, students can gather data quickly, and measurement errors and frictional effects can be explicitly controlled. This research investigates the relative support for students' learning offered by physical and virtual experimentation in the context of simple machines.

Specifically, I have investigated students' learning as supported by experimentation with physical and virtual manipulatives from three different angles-- *what* do students learn, *how* do students learn, and what do students *think about* their learning.

The results indicate that the virtual manipulative better supported students' understanding of work and potential energy than the physical manipulative did. Specifically, in responding to data analysis questions, students who used the virtual manipulative before the physical manipulative were more likely to describe work as constant across different lengths of frictionless inclined planes (or pulley systems) and were more likely to adequately compare work and potential energy, whereas students who used the physical manipulative first were more likely to talk about work and potential energy separately. On the other hand, no strong support was found to indicate that the physical manipulative better supported students' understanding of a specific concept.

In addition, students' responses to the survey questions indicate that students tend to value data from a computer simulation more than from a physical experiment. The interview analysis indicates that the virtual environment better supported the students to create new ideas than the physical environment did.

These results suggest that the traditional wisdom that students learn best from physical experiments is not necessarily true. Thus, researchers should continue to investigate how to best interweave students' experiences with physical and virtual manipulatives. In addition, it may be useful for curriculum designers and instructors to spend more of their efforts designing learning experiences that make use of virtual manipulatives.

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# Acknowledgements

Many friends and collaborators have contributed to this research.

I would like to thank my advisor, Sanjay Rebello, for piquing my interest in physics education research and guiding me through the years. Your support and encouragement have helped me to become a more confident research, speaker and teacher.

I would also like to thank Dr. Zollman and all the members of the Kansas State University Physics Education Research group (KSUPER) for the many types of assistance you have provided—serving as practice research subjects, participating in reliability and validity studies, attending my seminars, and sharing your ideas. I would especially like to thank Adrian Carmichael, Elizabeth Gire and Amy Rouinfar for your contributions to the curriculum development, study designs and implementations.

This research is the result of a collaboration between several universities, with many researchers, students, and support staff lending their unique talents to the project. I am very grateful for the contributions of Dr. Sadhana Puntambekar, the CoMPASS project leader, as well as all the members of the CoMPASS team. Special thanks to Garrett Smith for making our implementations possible even when we forgot to ask until the very last minute, and to Sarah Sullivan and Dana Gnesdilow for your insights on data analysis.

Thank you to Dr. Leigh Murray and Zhining Ou of the Kansas State University Statistics Department for sharing your knowledge and skills about statistical analysis.

Finally, I would like to thank my family and my husband Mike for their support through these years. Also, to Louis: thanks for putting up with me, even when I made you miss a walk!

# CHAPTER 1 - Introduction

This study was driven by the goal to compare how students' learning is supported by physical manipulatives, virtual manipulatives and a combination of physical and virtual manipulatives. In this study, the physical manipulatives were concrete, traditional laboratory equipment, such as spring scales, boards and pulleys, and the virtual manipulatives were computer simulations. Students' learning can be assessed in many ways and was approached in three specific ways in this study. First, I compared *what* students learned from activities using physical and/or virtual manipulatives. Second, I compare *how* students learned when using physical and/or virtual manipulatives. Third, I compared what students *think about* their learning when using physical and/or virtual manipulatives.

## 1.1 Motivation

Some work has already been done on the topic of comparing how students learn with physical and virtual manipulatives. However, previous studies, which are discussed in Chapter 2, leave much room for improvement. Many studies have included differences in instruction in addition to whether it is computer based or non-computer based (Klahr, Triona and Williams, 2007). More studies are needed that carefully control for confounding differences between students' learning with physical and virtual manipulatives. Additionally, previous studies have shown mixed results as to whether physical or virtual manipulatives better supported students' learning. Some studies have shown an added benefit of virtual manipulatives over physical manipulatives (for example, Zacharia, 2005; Finkelstein *et al*., 2005). Other studies, however, have shown no difference between students' learning when supported by these two types of manipulatives (for example, Klahr, Triona and Williams, 2007; Zacharia and Constantinou, 2008). More studies are needed to explore the reasons why these differences exist. Finally, Zacharia has called for an expansion of the contexts in which this question has been studied (Zacharia, Olympiou and Papaevripidou, 2008).

This study is also motivated by the practical concern of where we should be putting our efforts. Identifying when and why students' learning is better supported by physical or virtual manipulatives will help educational developers and teachers focus their efforts. For example, answers to these questions could help curriculum developers decide whether to design curricula for certain topics with physical or virtual manipulatives. Additionally, these answers could help classroom teachers decide how to have their students explore certain concepts.

## 1.2 Scope of Research

This study was funded in part by a U.S. Department of Education, Institute of Education Sciences Award R305A080507 entitled *Scaffolding Students' Use of Multiple Representations for Science Learning*. The goal of this grant was to develop a middle school simple machines curriculum that integrated scientific investigations (with both physical and virtual manipulatives), online hypertext concept maps, and design-based learning. The curriculum will be described in Section 2.8 of this dissertation. Thus, the physics content of these studies was limited to simple machines.

Within the topic of simple machines, I focused specifically on the physics of pulleys and inclined planes. This choice is sensible for several reasons. Pulleys and inclined planes are typically studied in introductory physics courses, so these topics should be of interest to the physics education community. In addition, this context presents several questions that are interesting to explore in terms of how students' learning is supported by experimentation with physical and virtual manipulatives. For example, since students can feel the force applied in a physical experiment, do the physical manipulatives better support their understanding of force? Since work is an abstract concept that cannot be directly felt in the physical experiment, do the virtual manipulatives better support students' understanding of work? Does the physical experience of constructing the inclined planes and pulleys in the physical experience appear to support students' understanding of these machines more than their experiences with the simulations? Finally, the contexts of pulleys and inclined planes does not seem to have been studied yet in terms of the support for student understanding provided by physical and virtual manipulatives.

Because these studies focus on the specific content areas of pulleys and inclined planes, a possible limitation to the study is the applicability of the results to other content areas. In addition, the population studied was limited to students enrolled in conceptual- or algebra-based introductory physics courses. Thus, the findings of these studies may not generalize to other populations. One goal of the grant supporting this research is to develop a simple machines curriculum for middle school students.  Typically, students enrolled in conceptual-based introductory physics courses have not studied much physics.   This population is useful for these studies as the students may have similar content knowledge about inclined planes and pulleys to the middle school students, but it is easier to control the curriculum in a college laboratory than in a middle school classroom.

## 1.3 Research Questions

In a broad sense, these studies aimed to compare what and how students learn from physical and/or virtual manipulatives as well as what they think about their learning from physical and/or virtual manipulatives.  The studies were designed to address the following research questions:

1) *What do students learn:* What do students learn from the physical activities, and what do they learn from the virtual activities?
    a) Do students' written responses to data analysis questions differ between the physical and virtual experiments or the physical-virtual and virtual-physical sequences?
    b) Do the physical and virtual manipulatives or physical-virtual and virtual-physical sequences provide different support for students' conceptual understanding?
    c) When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity?
2) *How do students learn:* Do the environments created by the physical and virtual manipulatives offer different support for dynamic transfer (or the creation on new ideas)? What features of each environment create the support?  Can the support offered by one environment be recreated in the other?
3) *What do students think about their learning:* Do students view the information from physical and virtual manipulatives differently?  Is there evidence that different epistemic resources (or resources for thinking about knowledge and knowing) are activated by the two contexts?

## 1.4 Research Strategy Overview

This study involved several distinct types of investigations, which align with the research questions above.  In order to address:

- Research Question 1 (i.e. what do students learn), the pulley and inclined planes curricula were used in introductory physics laboratories. Students performed activities with physical and/or virtual manipulatives, responded to written open-ended research questions, and completed multiple-choice tests. Both qualitative and quantitative research methods were used to analyze this data, as described more thoroughly in Chapters 3 and 4.
- Research Question 2 (i.e. how do students learn), individual learning/teaching interviews were conducted. The interviews were transcribed and analyzed with through a phenomenographic approach (Marton, 1986).
- Research Question 3 (i.e. what do students think about their learning), students views of the physical and virtual experiments and the data produced by those experiments were collected with survey instruments.

Table 1.1 below summarizes how the studies addressed the research questions and when the studies were conducted.

**Table 1.1 Research Strategy Overview**

| Research Question | Type of Study | Timeline |
|---|---|---|
| RQ1: What did students learn? | In-class implementations of pulley and inclined plane curricula | Spring 2009, Fall 2009, Spring 2010 |
| RQ2: How did students learn? | Individual teaching/learning interviews | Fall 2009 |
| RQ3: What did students think about their learning? | Surveys | Fall 2009, Spring 2010 |

## 1.5 Layout of Dissertation

This dissertation consists of 11 chapters. In this first chapter, I have described the motivation for and scope of this research as well as the research questions and research strategies. Chapter 2 describes the theories that have guided this research and the results of relevant previous research. Chapter 3 describes the research setting and qualitative and quantitative research methodology in detail; this chapter concludes with a discussion of how the research methods map onto the research questions. Chapter 4 describes each of the separate studies in detail, including study design, research instruments and analysis techniques. Chapter 4 concludes with a discussion of how the study design maps onto the research questions.

Chapters 5 through 10 present the data analysis. Chapter 5 presents the analysis of students' responses to the worksheet questions in the pulley studies from the in-class implementations, and Chapter 6 presents the analysis of students' performance on the conceptual tests in those same studies. Chapter 7 present the analysis of students' responses to the worksheet questions in the inclined plane studies from the in-class implementations, and Chapter 8 presents the analysis of students' performance on the conceptual tests in those same studies. Chapter 9 presents the analysis of how students learned (in terms of the framework for dynamic transfer, described in Section 2.5.2.4) during the individual learning/teaching interviews. Finally, Chapter 10 presents the analysis of students' responses to the survey questions about their views of experiments conducted with physical and virtual manipulatives.

Chapter 11 summarizes how these studies have addressed the research questions. In addition, Chapter 11 presents implications for future research, curriculum design and instruction.

# CHAPTER 2 - Review of Related Literature & Studies

## 2.1 Introduction

In this chapter, I summarize the literature and previous studies that have informed my research. I begin by summarizing some general aspects of learning. First, I describe the principle of constructivism, which forms the basis for the curricular materials used in this study. Then, I focus on the three aspects of student learning related to my research questions, namely conceptual understanding, epistemology and transfer of learning. This research takes a small-grained size approach toward viewing knowledge through each of these distinct lenses. Next, I turn to the literature about the specific aspects of comparing student learning with physical and virtual manipulatives. I first broadly explore the meaning of hands-on learning and potential advantages and disadvantages to using physical or virtual manipulatives. I then review prior studies on the effectiveness of physical and virtual manipulatives at promoting student learning in physics. Finally, I describe the basis and some research done on the CoMPASS curriculum, which is used in this study.

## 2.2 Constructivist Views of Learning

Constructivism (Bruner, 1966) is a theory of learning that presupposes that individual learners construct their own knowledge from their experiences and interactions with the environment. The knowledge that learners actively construct is influenced by their prior knowledge. In the constructivist view of learning, the teacher can only facilitate the learning process, not transmit knowledge directly to the students.

As explained by Philips (1995), many constructivist theories exist. I begin by describing Philips' (1995) framework for comparing different constructivist theories. As examining all of these theories is beyond the scope of this dissertation, I focus on the theories of Piaget and Vygotsky, as these theories are most typically used by science educators. Although these theorists agree that learning is an active process of construction, Piaget focuses more on cognitive development while Vygotsky focuses on social interaction. I then explain how Cobb's (1994) idea of "theoretical pragmatism" suggests that researchers can view Piaget and

Vygotsky’s ideas as not mutually exclusive.  I also discuss a few modern constructivist principles.

### *2.2.1 Comparing Constructivist Views*

Philips (1995) has suggested three dimensions along which different constructivist theories can be classified.  Philips labels the first dimension “individual psychology versus public discipline.”  Theorists at the “individual” extreme of this dimension are concerned with how an individual constructs his or her own knowledge, whereas those at the “public” extreme are not concerned with the individual learner, but rather how human communities construct bodies of knowledge.

Philips’ (1995) second dimension is labeled “humans the creators versus nature the instructor.”  This dimension asks the questions, “is new knowledge—whether it be individual knowledge, or public discipline—made or discovered?”  At the “humans the creators” end of this dimension are theorists who believe knowledge creation is brought about by an individual or group of learners.  On the other hand, theorists at the “nature the instructor” end of the dimension believe that knowledge is imposed on, passively copied, or absorbed by the learner from the outside world.  Philips cautions that it may be difficult to classify theorists on this extreme of the dimension as constructivists at all.

The third and final dimension of Philips’ (1995) framework deals with the process of learning.  One can view the activity of learning as governed by either individual cognition or social and political processes.  In addition, one can assume the activity of learning to be either physical or mental.  It has been suggested the label “transmission versus construction” for this dimension.  At the transmission end of the spectrum are theorists who believe that a learner can passively receive information.  However, as opposed to the behaviorist view of knowledge, these theorists require that the learner internalize the information in some way.  At the construction end of the dimension, theorists view learners as engaged in a dynamic process of learning.  See Figure 2.1 for a visual representation of Phillips’ dimensions.

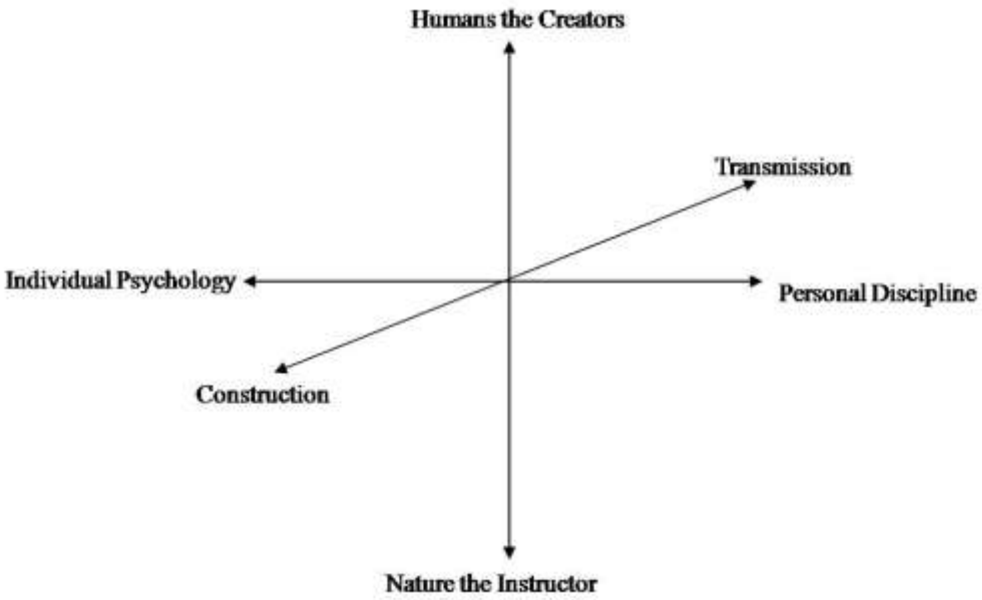


**Figure 2.1 The dimensions of constructivism as described in Phillips' (1995) framework.**

### *2.2.2 Piagetian Constructivism*

Piaget's (1964) theory focuses on cognitive development. He saw development as occurring in four major stages—sensory-motor, pre-operational, concrete operational, and formal operational. He believed children progressed through these stages of development at particular ages. The first or sensory-motor stage is pre-verbal, so knowledge is based on motor activity rather than symbols. In this stage, children develop the practical knowledge, such as object permanence and temporal succession, that will shape their later knowledge. In the second or pre-operational stage, children begin to use language and symbols to demonstrate knowledge, but still lack conservation reasoning and thus also lack an understanding of reversible operations. In the third or concrete operational stage children's reasoning becomes logical, but only in relation to concrete objects. Children in this stage can perform the operations of classification and ordering, and the fundamental operations of elementary logic, mathematics, and physics. Finally, in the fourth or formal operational stage, children are capable of both hypothetical and concrete reasoning.

Although Piaget associated these stages of development with a child's age, most educators who have used Piaget's ideas disagree. For example, Karplus (1977) discussed a study that found students acted in a concrete operational mode in one domain but in a formal operational mode in another. Thus, it is not safe to assume that even adults will act in a formal operational mode in all domains. It is possible for an individual to exhibit formal operational reasoning in a domain where he or she has a certain degree of expertise, but to exhibit concrete operational reasoning in other less familiar domains.

Piaget’s (1964) theory of learning describes the learning process in terms of schemas, assimilation and accommodation. Schemas govern how a person interacts with and gains knowledge of the world. Schemas allow a person to mentally represent objects and events in the world (Woolfolk, 2001). Assimilation and accommodation are the two basic processes involved in changing one’s knowledge structures. Assimilation occurs when new knowledge is incorporated into the existing schema without requiring reorganization of the existing schema. However, new information does not always fit into the existing schema without reorganization. In this case, accommodation must occur and the schema must be changed. Assimilation and accommodation will be discussed more in the context of conceptual change.

In this research, I did not assume that students are in one of the particular stages described above. Rather, I analyzed students’ reasoning through interviews and written responses without assuming they operate in a particular mode. In fact, it is likely that students will shift from concrete operational to more formal operational reasoning as we provide them with various learning experiences.

### *2.2.3 Vygotskian Constructivism*

Vygotsky (1978) saw social interaction as the primary process of development. One of the key concepts of Vygotsky’s theory is the Zone of Proximal Development (ZPD). Although a person’s actual developmental level only refers to the functions and activities he or she can perform alone, the ZPD also includes the functions and activities the person can perform with the help of a more knowledgeable other, such as an adult or more capable peer. (See Figure 2.2 for a visual representation of the ZPD.) At the core are the activities that the student can perform alone without outside assistance. In the outer ring are the activities the student cannot perform at this time even with outside assistance. The space between is the ZPD and is made up of the activities the student can perform with the assistance from a more knowledgeable other. Bruner (1966) has referred to the assistance provided by the more knowledgeable other as scaffolding. After the scaffolding has helped the learner to increase his or her actual developmental level, the learner should be able to perform the functions and activities with the scaffolding removed. In terms of Figure 2.2, this would mean that the inner circle expands to include activities that once resided in the ZPD.

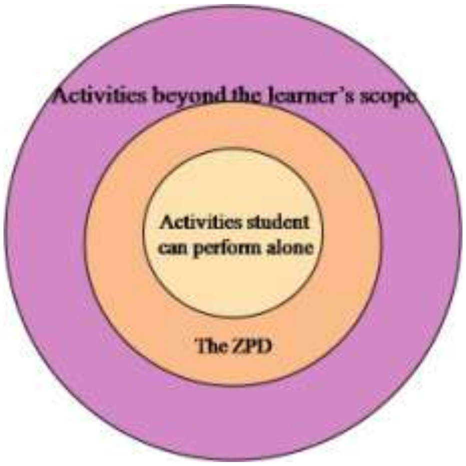


**Figure 2.2 A visual representation of the Zone of Proximal Development (ZPD).**

Tharp and Gallimore (1991) have identified four stages to knowledge construction based on the ZPD. In the first stage, the learner is assisted by a more knowledgeable other; scaffolding is provided to increase the learners' proportion of task participation and responsibility. In the second stage, the learner performs the task without the help of the more knowledgeable other, but has not yet completely mastered the task. In the third stage, the learner masters the task by internalizing what has been learned. In the fourth stage, the learner discovers a task that he or she could formerly perform is no longer possible and the learner must return to the first stage. For example, the task may have become impossible due to a change in context. See Figure 2.3 for a visual representation of these stages.

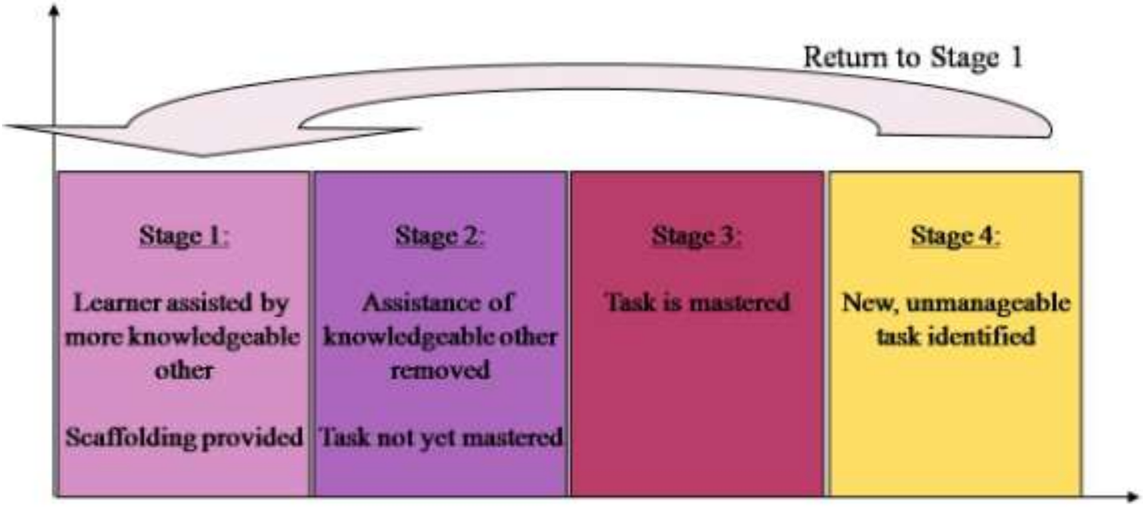


**Figure 2.3 Tharp and Gallimore's stages of knowledge construction.**

In this research, several forms of scaffolding, including activities, prompts, guidelines and questions, are used to help facilitate knowledge construction about simple machines. The particular scaffolds used will be discussed in detail in later chapters.

### *2.2.4 Integrating Piaget and Vygotsky*

While the Piagetian and Vygotskian views of constructivism both highlight the importance of active learning, the Piagetian perspective puts primary emphasis on the individual while the Vygotskian perspective puts primary emphasis instead on the socio-cultural context. Piagetian theorists look at learning in terms of cognitive processes in an individual's mind, whereas Vygotskian theorists look at learning in terms of an individual in conjunction with an exterior context. Cobb (1994) proposes the idea of "theoretical pragmatism" in which he combines elements of Piagetian and Vygotskian constructivism in ways that are not mutually exclusive. Cobb explains that although the two views see different mechanisms at work in the construction of knowledge, in both cases the learner must internalize the knowledge that has been constructed. This implies that the perspectives are not mutually exclusive. Rather, each has independent value in examining learning. For example, a Vygotskian researcher might investigate how a novice appropriates a cultural form, but would have difficulty explaining how a cultural form can become a cognitive form. However, a Piagetian researcher could describe this process by emphasizing that the novice reorganizes his or her own activity rather than simply internalizing a given cultural form. Thus, Cobb states that while one perspective may be at the forefront of a particular analysis, commitments to the other perspective are present in the background. This is the point of view adapted in this research.

Returning to Philips' dimensions for comparing constructivist theories, Piaget and Vygotsky occupy similar space in the framework presented in Figure 2.1. On the first dimension, Vygotsky and Piaget would both be located toward the individual end as they were both focusing on individual learners, although they saw different mechanisms at work in the knowledge construction process. While Piaget focused on the biological and psychological factors at work within an individual learner, Vygotsky focused on the social factors involved in learning. On the third dimension, Piaget and Vygotsky would both be located toward the construction end of the spectrum. It is on the second dimension that the theorists differ, as Piaget believed cognitive development occurred with natural age development, while Vygotksy believed social factors played an important role.

### *2.2.5 Some Current Constructivist Principles*

Redish (1999) has listed five general principles based on what psychologists and educators have learned about teaching and learning. Three of the principles are associated directly with constructivism and how it should be implemented. The constructivism principle states "individuals build their knowledge by processing the information they receive, building patterns of association to existing knowledge" (Redish, 1999, p. 564). This principle clearly states that learners must construct their own knowledge and describes the mechanism for learning as adding new associations into existing knowledge. The context principle states "what people construct depends on the context—including their mental states" (Redish, 1999, p. 564). This principle warns that the context in which students learn material affects what they learn. Even more, it is not just the exterior context, but also the students' mental states, such as prior knowledge and beliefs about learning, that affect what they learn. Finally, the change principle states "producing significant change in a well established pattern of associations is difficult but can be facilitated through a variety of known mechanisms" (Redish, 1999, p. 564). Thus, we should not assume it is easy to change students' knowledge, but strategies exist to make the process easier. Some of these strategies for conceptual change are discussed below.

An understanding of these principles is essential for designing successful learning materials, such as those that were explored in these studies. The materials used are designed with the awareness that students must build their own knowledge; the role of the materials is to facilitate knowledge construction, not to transmit knowledge directly. I believe the context principle and change principle are important to study in the context of learning from physical and virtual manipulatives. The type of manipulative used to support learning makes up part of the learning context, so it is possible that students will learn differently in these two contexts. Also, the experiences afforded by the physical and virtual manipulatives are different, which may give them different opportunities to promote conceptual change.

In this study, I took a view similar to both Piaget and Vygotsky. I took the view that knowledge is possessed and constructed by individuals, looking both at the psychological factors, as did Piaget, and the social factors, as did Vygotsky. Additionally, I adopted the perspective, as did Piaget and Vygotsky, that learners must engage in a dynamic process of learning.

## 2.3 Conceptual Understanding

One of the goals of this research project is to describe what students learn from the physical and virtual learning environments. This analysis was shaped by my view of students' conceptual understanding. While physics education research had a narrow focus on student misconceptions or difficulties for many years (Hammer, 2000), more recently researchers have begun to describe the structure and behavior of students' knowledge elements. These new theories go beyond research on student misconceptions by allowing for some form of useful naïve notions. An important difference among these theories is the grain size they assign to those notions. Below, I describe several current views of conceptual understanding that are important to this research.

### *2.3.1 Phenomenological Primitives*

DiSessa (1993) proposed phenomenological primitives (p-prims) as a possible knowledge structure. P-prims are small in grain size and are used to explain other phenomena. P-prims do not require justification because they are ideas that "just make sense" to the learner. P-prims are activated by a physical system or the system's behavior. Learners may use p-prim reasoning in a variety of situations. P-prims are not inherently correct or incorrect, but can be applied correctly or incorrectly. For example, a primitive such as "closer means stronger" accurately describes light being more intense closer to a light bulb, but could lead to the incorrect explanation of why summer is hotter than winter as the earth being closer to the sun (Hammer, 2000).

DiSessa chose the term “phenomenological” to emphasize that p-prims are derived from everyday experience and build up the basis on which we remember and interpret experiences. The term “primitive” was likewise chosen to emphasize that p-rims are self-explanatory and likely the most atomic and isolated knowledge structure. As an example, consider “Ohm’s p-prim”. Ohm’s p-prim explains the interaction of effort, resistance, and result, such as more effort means more result or more resistance means less result. We can see how this p-prim can arise from everyday experience, such as pushing a chair across the floor. Other p-prim examples provided by diSessa include “force as mover” (objects move in the direction of a push), “blocking” (a moving object may be stopped by another object in it’s path) and “warming up” (change takes time). In summary, p-prims are small, isolated knowledge chunks that arise from our everyday experiences so they “just make sense” and do not require additional justification.

In this research, students’ reasoning, especially before instruction, may be based on p-prims. It is interesting to consider p-prims in the context of student learning in the physical and virtual environments as different p-prims may be activated by the different environments.

### *2.3.2 Resources*

David Hammer (2000) describes students as having “resources” from which they construct new knowledge. A useful analogy for conceptual resources is a computer resource, or chunk of computer code that gets used in a larger computer program to perform a function. In much the same way, mental phenomena like thinking and reasoning result from many resources working together. Conceptual resources differ from misconceptions in several ways. In the misconception framework, students’ reasoning is viewed as the result of single cognitive elements that are either consistent or inconsistent with the expert understanding. However, in the resources framework, students’ reasoning results from the activation of many smaller grained resources. Hammer views resources along a varying grain-size, which includes diSessa’s p-prims. Like p-prims, each resource itself is not classified as right or wrong; rather, a particular resource could be activated in a context to which it does not correctly apply. The activation of resources is context-dependent.

Studying students' conceptual understanding through the lens of resources is an alternative to studying their misconceptions or difficulties. The misconceptions framework does not provide an account of students' productive resources and does not explain why reasoning varies with context. On the other hand, the resources framework provides a form of the raw material from which students construct new knowledge. The resources framework can be used to explain difficulties and misconceptions. In this view, a difficultly is the tendency to misapply resources and a misconception is a robust pattern of misapplying resources. While misconceptions tend to be thought of as stable, students may use resources to dynamically construct their understanding in a particular context.

As with p-prims, it is interesting to study resources in the context of the physical and virtual manipulatives. Students in these studies will use resources to build their understanding of the physics of simple machines, and it is possible that different resources will be activated by the physical and virtual manipulatives.

### *2.3.3 Coordination Class*

A coordination class is a knowledge structure proposed by diSessa that explains how we get a certain kind of information from the world (diSessa and Sherin, 1998). A coordination class is of larger grain size than both p-prims and resources and can be broken down into two categories based on function: "readout strategies" and the "causal net". Readout strategies are the way people get a certain type of information from a context. Types of information could include the defining attributes of a concept or the value of a quantity in a particular situation. The causal net consists of the knowledge and reasoning strategies that allow an individual to know when and how observations are related to information, or how to turn readout information into the desired information. For example, someone with an understanding of Newton's second law may use his casual net to recognize that the acceleration "readout" from a certain situation can help him to find the force in that situation. DiSessa and Wagner (2005) explain that students may encounter two classes of difficulties related to reading out the same information from a variety of contexts while constructing and applying a coordination class. The problem of "span" states that an individual must acquire enough knowledge to apply the concept in a wide range of contexts. The problem of "alignment" states that an individual must determine the same information from a variety of contexts.

The curriculum used in this study aims to help students develop a coherent understanding of physics concepts, such as force, work and mechanical advantage. This coherent understanding can be viewed as a coordination class.

### *2.3.4 Conceptual Change*

As stated above, it is not an easy task to change the state of students' knowledge. However, researchers have developed various theories to explain how the process of conceptual change can be facilitated. I describe a few of these theories below.

As described above, Piaget (1964) described learning in terms of assimilation, where accepting new information does not necessitate reorganizing existing knowledge, and accommodation, where changes to existing knowledge are necessary in order to accept new information. Posner *et al*. (1982) describe the essential conditions for the more difficult process of accommodation to occur. It is important to note that while Posner *et al.* use Piaget's words, they do not commit themselves to his theories. First, students must become dissatisfied with their conceptions; this could involve identifying problems that their current knowledge state cannot explain or solve. Second, the new concept must make sense. Metaphors or analogies may be useful in helping students make sense of the new concept. Third, the new concept must appear to solve the problems left unsolvable by the initial knowledge state. Finally, the new concept should suggest its potential for extending to solve other problems or open new areas of inquiry. Posner *et al*. defined these conditions largely from the philosophy of science, and assert that students (in the process of learning) engage in the same processes as practicing scientists. This commitment is not shared in this dissertation. While some learning may occur in this manner, I do not assume that all students engage in learning through the same processes as practicing scientists.

Several more recently developed strategies for conceptual change are a better fit with Hammer's description of conceptual resources, which has been adopted in this study. One example is Brown and Clement's "bridging strategy" (1989). Clement, Brown and Zietsman (1989) assert that some of students' preconceptions are in alignment with accepted physical theory; they call these physically correct preconceptions "anchoring conceptions" or "anchors." These anchors can be extended through the use of bridging analogies to a target case, where the student's preconception is not physically correct. For instance, while students may have difficulty understanding that a table exerts an upward force on a book resting on it (the target case), they do understand that a compressed spring exerts an upward force on their hand (the anchor). Bridging analogies can be used to help students understand that even a rigid object like the table has some springiness, thus making a believable analogical relation between the anchor and the target. See Figure 2.4 for a visual representation of the bridging strategy.

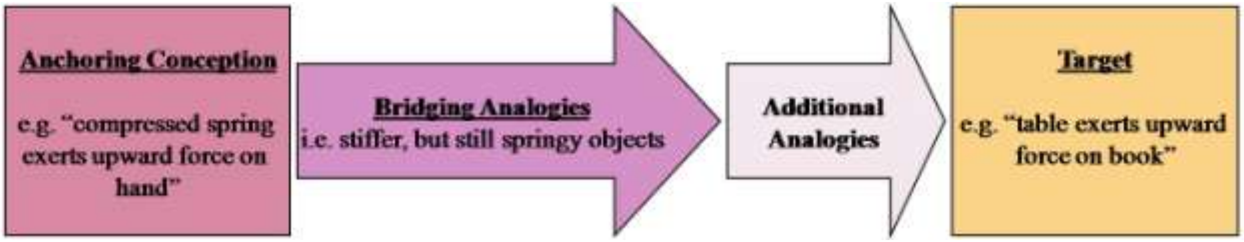


**Figure 2.4 The stages of Brown and Clement's (1989) bridging strategy.**

Another example of a strategy for conceptual change that makes use of students' productive resources is described by Elby (2001). Elby's strategy involves refinement of students' "raw intuition" to a more coherent understanding. For example, in the case of a car colliding with a truck that has twice the mass of the car, many students have the raw intuition that the "car reacts twice as much." The idea of "reacting" twice as much could be incorrectly applied to the force exerted on the car during the collision or the car's acceleration during the collision. The process of refining students' raw intuition involves walking students through the implications of applying their idea of reaction to force or acceleration. See Figure 2.5 for a visual representation of refinement of raw intuition.

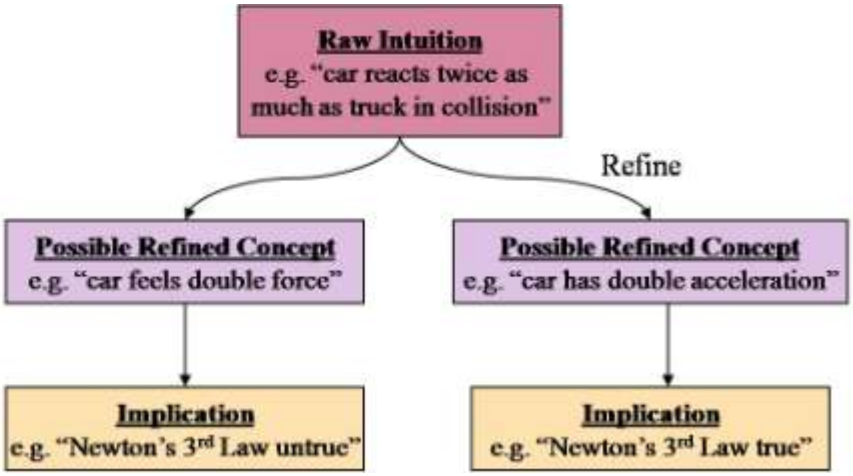


**Figure 2.5 Elby's strategy of refining raw intuition.**

Analysis of the process of conceptual change is beyond the scope of this research. I focus on the end result of the conceptual change by analyzing what knowledge students build from their experiences with the physical and virtual manipulatives. Still, it is important to note that the strategies of bridging analogies and refinement of intuition are consistent with the resources approach to student understanding adopted in this research.

## 2.4 Epistemology

A student's personal epistemology describes his or her beliefs about the nature of knowledge and knowing. Personal epistemology includes students' beliefs about what knowledge is, how something is known, how knowledge is evaluated, and the source of knowledge (Hofer, 2001). Hammer and Elby describe personal epistemology as "a category of informal knowledge that may play a role in students' knowledge, reasoning, study strategies and participation" (2002, pg. 169). As personal epistemology affects how students evaluate new knowledge and choose between discrepant knowledge claims, this is an important topic to study in the context of learning through physical and virtual experimentation. It is possible students will evaluate information from these sources differently and may show favor to knowledge from a particular source.

The study of epistemology has mirrored the study of conceptual understanding in the transition from focusing on misconceptions to productive resources. For many years, students were believed to possess stable epistemic "beliefs" and research focused on students "misbeliefs" about physics knowledge and learning (Hammer, 2000). Below, I describe a few traditional models of epistemology, including Perry's development model (1970), Schommer's (1990) independent beliefs model, and Hofer's (2000) epistemological theories. Then I describe Hammer and Elby's (2002) contemporary, resources based approach to student epistemology, which is adopted in this study.

### *2.4.1 Developmental Model of Personal Epistemology*

Developmental models of personal epistemology suggest that individuals progress through a systematic development in their beliefs about knowledge (Hofer, 2001). Developmental models are based on Piaget's work and emphasize children's cognitive development with respect to the relationship between the knower and the known (Hofer, 1997). Commonly, developmental models of personal epistemology state that individuals start with the belief that knowledge is objective and certain. Individuals progress to recognizing that knowledge may be uncertain and opposing ideas may hold validity, eventually learning the importance of supporting evidence and gaining the ability to weigh opposing ideas. In the final stage, learners are able to construct their own justified knowledge.

The classic developmental model of epistemology was developed by Perry (1970). Perry's model, based on interviews with Harvard college students, includes four stages, similar to those described above. The beginning stage is the *dualistic* perspective, where individuals view knowledge as definitely right or wrong and believe it is the teacher's responsibility to communicate knowledge. This develops into *multiplism*, where individuals allow for the possibility of uncertainty and may see conflicting views as equally valid. The next stage is *relativism*, where individuals can recognize some views as better than others. In the final stage, *relativism with commitment*, students continue this development, and the development changes from intellectual to ethical in nature. See Figure 2.6 for a visual representation of Perry's developmental model.

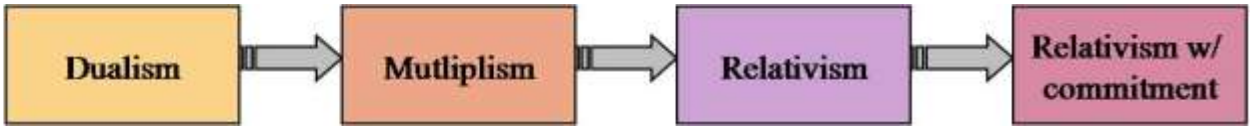


**Figure 2.6 The stages of Perry's developmental model.**

Additional developmental models expanded the participants studied to include women and others from diverse backgrounds (Buehl and Alexander, 2001). Examples include "women's ways of knowing" (Belenky, Clinchy, Goldberger and Tarule, 1986; Goldberger, Tarule, Clinchy and Belenky, 1996), the Epistemological Reflection Model (Baxter Magolda, 1992), reflective judgment (King and Kitchener, 1994) and the levels of epistemological perspective in argumentative reasoning (Kuhn, 1991). In this research, I did not assume that students are in any particular stage of epistemological development.

### *2.4.2 Independent Beliefs Model*

Another approach to personal epistemology views the form in terms of independent beliefs, rather than a developmental process. Schommer (1990) pioneered this approach with her Epistemological Beliefs Questionnaire, which identified four dimensions to students' personal epistemology. The first dimension deals with the certainly of knowledge, with students expressing ideas from the naïve perspective that knowledge is certain to the expert perspective that knowledge is tentative. Another dimension covers the simplicity of knowledge, ranging from the naïve idea that knowledge is isolated to the expert perspective that knowledge is highly interrelated. The final dimensions are quick learning, which ranges from the belief that learning occurs quickly to learning occurs gradually, and innate ability, which ranges from viewing intelligence as fixed to viewing intelligence as incremental. See Figure 2.7 for a visual representation of Schommer's model of independent epistemic beliefs. In this research, I did not assume that students' beliefs along these dimensions remained constant during the various learning experiences.

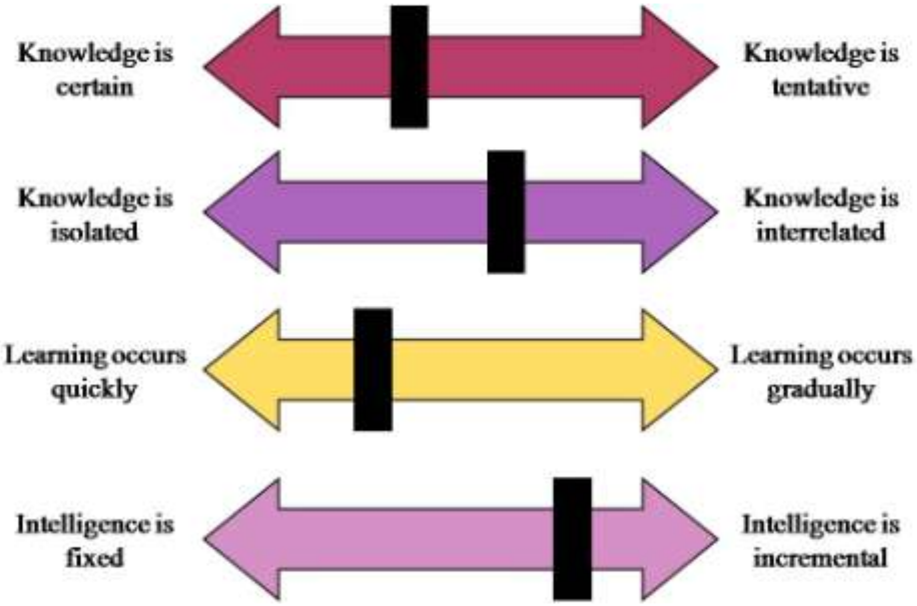


**Figure 2.7 Schommer's model of independent epistemic beliefs.**

### *2.4.3 Epistemological Theories*

After a review of the prior research on personal epistemology, Hofer and Pintrich (1997) proposed the construct of epistemological theories. Epistemological theories models share the idea of multidimensionality with independent beliefs models, such as Schommer’s. However, they abandon the independence of those beliefs in favor of an interconnected, coherent personal theory (Hofer, 2001). This view implies there is more integration of beliefs within a particular student. Additionally, the model allows for discipline-specific epistemological assumptions. Hofer (2000) has identified two categories of epistemology: nature of knowledge, which includes certainty and simplicity of knowledge, and nature of knowing, which includes source and justification of knowledge. See Figure 2.8 for a visual representation of Hofer and Pintrich’s model of epistemological theories. This representation highlights that Hofer views students’ ideas about certainty and simplicity of knowledge as grouped into a theory about the nature of knowledge and source of knowledge and justification for knowing as grouped into a theory about nature of knowing. This is in contrast to Schommer’s epistemic beliefs model where each dimension is independent of all other dimensions.

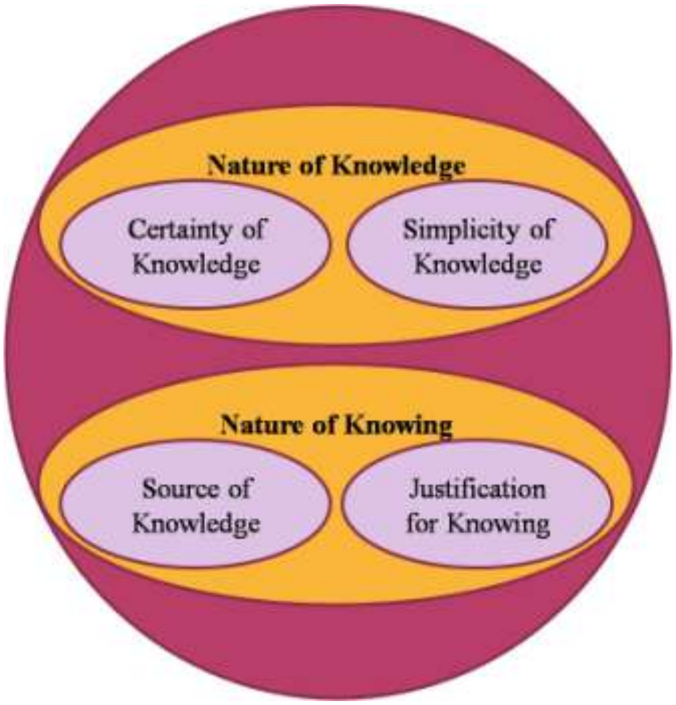


**Figure 2.8 Hofer and Pintrich's model of epistemological theories.**

In this research, I took the stance that students' personal epistemologies may shift, as is suggested by the discipline-specific nature of epistemological assumptions.  However, I did not assume that students have a coherent theory of epistemology.

### *2.4.4 Epistemic Resources*

Hammer and Elby (2002) describe their view of the form of student epistemology in terms of epistemic resources.  Hammer (2000) describes epistemic resources similar to his view of conceptual resources.  Just as conceptual resources are of a smaller grain-size than misconceptions, epistemic resources are smaller grained than beliefs.  Also, epistemic resources are activated or deactivated in certain contexts, as are conceptual resources.  As an example, Hammer points out that many students seem to hold the view that science knowledge comes from authority.  Yet we know that in other contexts, the same students are able to view knowledge as invented (making up the name of a doll) or inferred (figuring out someone is hiding a present under their coat).

Hammer and Elby (2002) explain several characteristics they expect to hold true for all epistemic resources.  Epistemic resources should be recognizable to young children, should have plausible developmental origins, and should be identifiable as “common-sense” mini-generalizations about knowledge.  Hammer and Elby have also suggested several possible categories of epistemic resources.  One category is made up of resources for understanding the nature and sources of knowledge or how to answer the question “How do you know?”  As stated above, possible resources in this category include knowledge is propagated stuff or transmitted, knowledge is free creation or invented, and knowledge is fabricated or inferred.  A second category includes resources for understanding epistemological activities or answering the question “What are you doing?”, such as accumulation or finding out, formation or self-constructing, application or using existing knowledge, and checking.  Another category is made up of resources for understanding epistemological forms, such as stories, rules and facts.  The final category includes resources for understanding stances taken toward knowledge, such as belief, disbelief, doubting, understanding and accepting.  See Table 2.1 below for a summary of these categories of epistemic resources.

**Table 2.1 Summary of Categories of Hammer and Elby's (2002) Epistemic Resources**

| **Category: Resource for Understanding…** | **Examples of Resources** |
|---|---|
| The nature and source of knowledge | Knowledge is propagated stuff, Knowledge is free creation, Knowledge is fabricated |
| Epistemological activities | Accumulation, Formation, Application, Checking |
| Epistemological forms | Stories, Rules, Facts |
| Epistemological stances | Belief, Disbelief, Doubting, Understanding, Accepting |

Epistemic resources are activated or not activated within a given context.  Several resources within the same category may be activated at once.  For example, when thinking about a rumor, an adult could use both “knowledge is propagated stuff” and “knowledge is fabricated stuff” to understand the rumor’s spread and evolution (Hammer and Elby, 2002).  In addition, resources across categories may be activated at the same time, and in fact resources in different categories may be linked and may frequently activate together.  For instance, when the resource “knowledge is propagated stuff” is activated, it may trigger the resource “accumulation.”

Figure 2.9 displays a possible visual representation of epistemic resources.  Differently colored circles represent different categories of epistemic resources.  An individual may have a variety of resources within each category, but a particular context will activate particular resources.

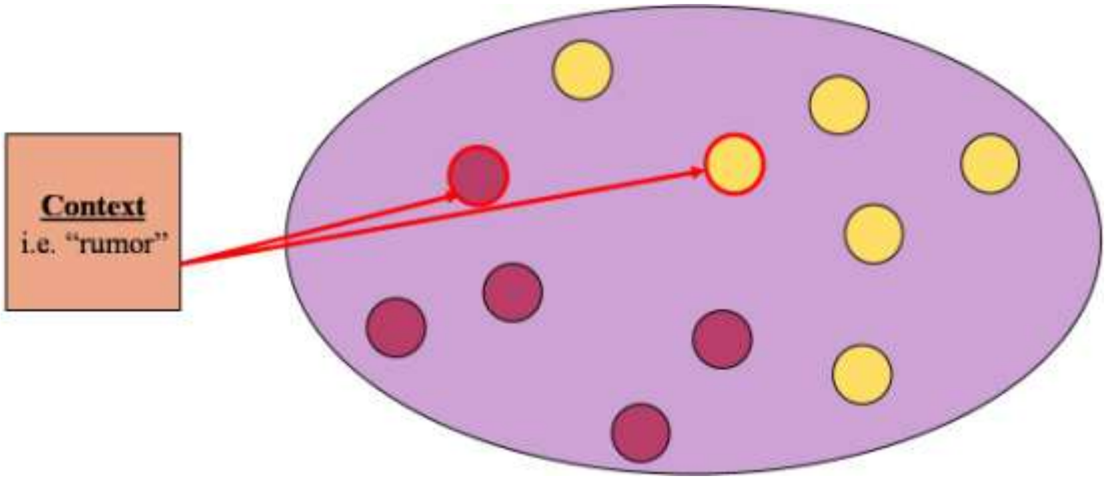


**Figure 2.9 A visual representation of epistemic resources.**

Just as the conceptual resources framework can be used to explain student misconceptions and difficulties, the epistemic resources framework can be used to explain the findings of prior studies of students' personal epistemologies. Take for example Schommer's findings of the dimension "Simple Knowledge," where students view knowledge as either isolated or interrelated. These results could be explained as an activation of certain resources, such as "rules," "facts" and "names," and deactivation of other resources, such as "categories" and "rule systems," in the context of Schommer's study (Hammer and Elby, 2002).

Hammer and Elby's theory of epistemic resources is the best fit for this research. The context-dependency allowed me to investigate whether different epistemic resources are activated in the contexts of the physical and virtual manipulatives.

## 2.5 Transfer of Learning

In this section, I describe the traditional view of transfer of learning as well as several contemporary views. While the traditional definition of transfer of learning was specific and rigid, the contemporary views have expanded the realm of possibilities of what "counts" as transfer. I spend the most time explaining Schwartz *et al.*'s (2008) view of dynamic transfer since it forms the basis of one of the research questions in this study.

### *2.5.1 Traditional View of Transfer*

Traditionally, transfer of learning has been described as taking information learned in one context and applying it to a new context (Reed, 1993; Singly and Anderson, 1989). This model of transfer typically requires the researcher to pre-determine what should transfer from the learning setting to the target setting and to look for evidence of transfer in the target setting. Bransford and Schwartz (1999) have described traditional transfer studies as "sequestered problem solving" because these studies typically place participants in a "sequestered" environment and deprive them of both access to any information besides what they have previously learned and the ability to learn by trial-and-error. These types of studies are generally static, one-shot assessments and typically find transfer to be rare (Rebello, 2007).

I kept the common goal with traditional transfer that students will acquire a predetermined (by physical correctness) knowledge state. However, I was open to analyzing students' responses for additional elements they may transfer from the learning situations, as discussed below.

### *2.5.2 Contemporary Views of Transfer*

Some contemporary models of transfer have moved beyond the static, one-shot assessment described above (Rebello, 2007). These models take into account social aspects of transfer, and tend to look at transfer from the student's point of view rather than that of the researcher. Thus, the researcher does not predetermine what should transfer, but analyzes the students' responses to see what students did transfer. These models are more dynamic and active and find transfer to be much more common, if not ubiquitous. A few specific contemporary views of transfer are described below.

#### *2.5.2.1 Lobato's Actor-Oriented Transfer Model*

One contemporary view of transfer is Lobato's actor-oriented transfer model (Lobato, 2003). In the traditional model of transfer, the researcher predetermines what students should transfer. However, in the actor-oriented model the researcher assumes each student has made connections between the situations and tries to identify which connections students make, why they make those connections, and whether the connections are productive. The two models define transfer differently. Whereas the traditional model defines transfer as applying knowledge learned in one setting to a new setting, the actor-oriented model defines transfer as "the personal construction of relations of similarity across activities" (Lobato, 2003, pg 20).

The model of transfer one uses affects what research questions can be asked, the research method that should be used and what transfer tasks can be given. With the traditional transfer model, it is appropriate to ask whether transfer occurred and what conditions helped it occur. However, since the actor-oriented transfer model assumes students are constantly creating connections between situations, we instead ask what connections were made and how the environment supported those connections. A traditional transfer task would be paired with a learning task with which it is assumed to have different surface features but shared structural features. On the other hand, the actor-oriented transfer model suggests that experts and learners may not agree on the task's surface and structural features. A researcher using the traditional transfer model accepts improved performance on the transfer task as evidence of transfer. However, a researcher using the actor-oriented transfer model expects that transfer will occur, and instead looks for influences from students' prior learning and the processes used to create connections between situations.

I took an actor-oriented approach in these studies to look for what ideas and skills students transfer into the learning situation as well as what they transfer across learning situations. While the goal learning state is predetermined by physical correctness, different students may use different ideas and skills to reach that final state.

#### *2.5.2.2 Greeno's View of Transfer of Situated Learning*

Greeno, Moore, and Smith (1993) assert that learning is shaped by the situation in which it occurs. Thus, they explain knowledge "is not an invariant property of an individual… knowing is a property that is relative to situations, an ability to interact with things and other people in various ways" (pg. 99). This view of learning makes transfer a social issue because an individual's interaction with the environment and other participants will shape what features the individual attends to and how he or she tries to relate the new situation to previous experiences.

An important aspect of Greeno *et al.*'s theory is the concept of "attunement to affordances". They define an affordance as "support for particular activities created by relevant properties of the things and materials in the situation" (pg. 102). Students are attuned to a specific affordance if they recognize that a particular activity is possible in a situation. A student's ability to identify a possible activity may depend on the skills and ideas a student has transferred into the situation. For example, consider a person sitting in an unfamiliar room. The person looks around the room and notices several openings, which he recognizes as doors and windows. He is attuned to the affordance of the door that it will allow him to exit the room. Now consider there is a fire blocking the door and it can no longer be used to exit the room. The person can transfer the idea that an opening can be used to exit the room to recognize the affordance that the window can also be used to exit the room.

Attunement to affordances is an important topic to consider in these studies since students will be learning in two different environments, one physical and one virtual. It is possible the two environments may provide different affordances or that students are differently attuned to the affordances each offers.

#### *2.5.2.3 Rebello et al.'s View of Dynamic Transfer*

Rebello *et al.* (2005) developed a framework to describe the process of transfer as it dynamically occurs during an interview. They identified four important elements to the framework. First, external inputs are the questions, hints, clues and materials that prompt transfer. Second, tools are the prior experiences and knowledge that are transferred into the new situation. Consistent with the theories of Lobato (2003) and Greeno *et al.* (1993), Rebello *et al.* state that the researcher should not predefine what the student transfers and include information about affordances as well as knowledge structures as potential tools that students may transfer. Additionally, epistemic resources (Hammer and Elby, 2002) may act as "meta-tools," affecting the type of cognitive tools students transfer. Third, the component the authors call the "workbench" includes the mental processes, such as making connections between tools, reorganizing knowledge, reasoning, and decision-making. The workbench emphasizes that students actively and dynamically build relations and similarities in a transfer context and do not transport these associations directly from the learning context. Fourth, the answer is the stopping point in the reasoning process, and may be decisive (arrives at a single conclusion), indecisive (unable to choose between answers, requests more information) or none (does not know). These elements are summarized the Table 2.2 below.

**Table 2.2 The Elements of Rebello *et al.*'s (2005) Model of Dynamic Transfer**

| **Element** | **Description** | **Examples** |
|---|---|---|
| External input | Answer the question: "What prompts transfer" | Questions, Hints, Pictures, Demonstrations |
| Tools | Answer the question: "What transfers?" | Prior experience and knowledge, Information about affordances |
| Workbench | Mental processes that use external inputs and tools | Making connections between tools, Reorganizing knowledge, Reasoning |
| Answer | Stopping point in reasoning | Single conclusion, Request for more information, "I don't know" |

Rebello *et al.* (2005) describe transfer as "a dynamic creation of associations between target tools read out from various external inputs and source tools activated from long-term memory" (pg 228). Source tools are students' preexisting knowledge and experiences. On the other hand, target tools are the attributes of the transfer context that the student uses to define that context in their mind. Greeno *et al.*'s (1993) affordances are an example of a target tool. Figure 2.10 below provides a visual representation of this model of transfer. External inputs may activate epistemic "meta-tools" from the student's long-term memory. The activated epistemic meta-tool controls the information the student reads-out from the transfer situation to be used as a target tool. Then, the epistemic meta-tool activates source tools from the student's long-term memory. The student then forms associations between source tools and target tools. The source-target tool association may cause the student to rethink the problem or may yield a new tool that is stored in the long-term memory.

Rebello *et al.*'s model of dynamic transfer was useful in this research. I looked for the associations that learners make between the information they readout while performing physical and virtual experiments and physics concepts. For example in the context of inclined planes, a student may associate less required input force with a longer board or she may associate less force with a less steep incline. Similarly, in the context of pulleys, a student may associate less force with the number of pulleys or may associate less force with the number of supporting strands supporting strands. In both examples, the latter association would be more productive for explaining the physics of the simple machine. Since the external input changed when the students performed experiments with physical and virtual manipulatives, it is interesting to identify the associations student make and whether those associations vary between the two learning situations.

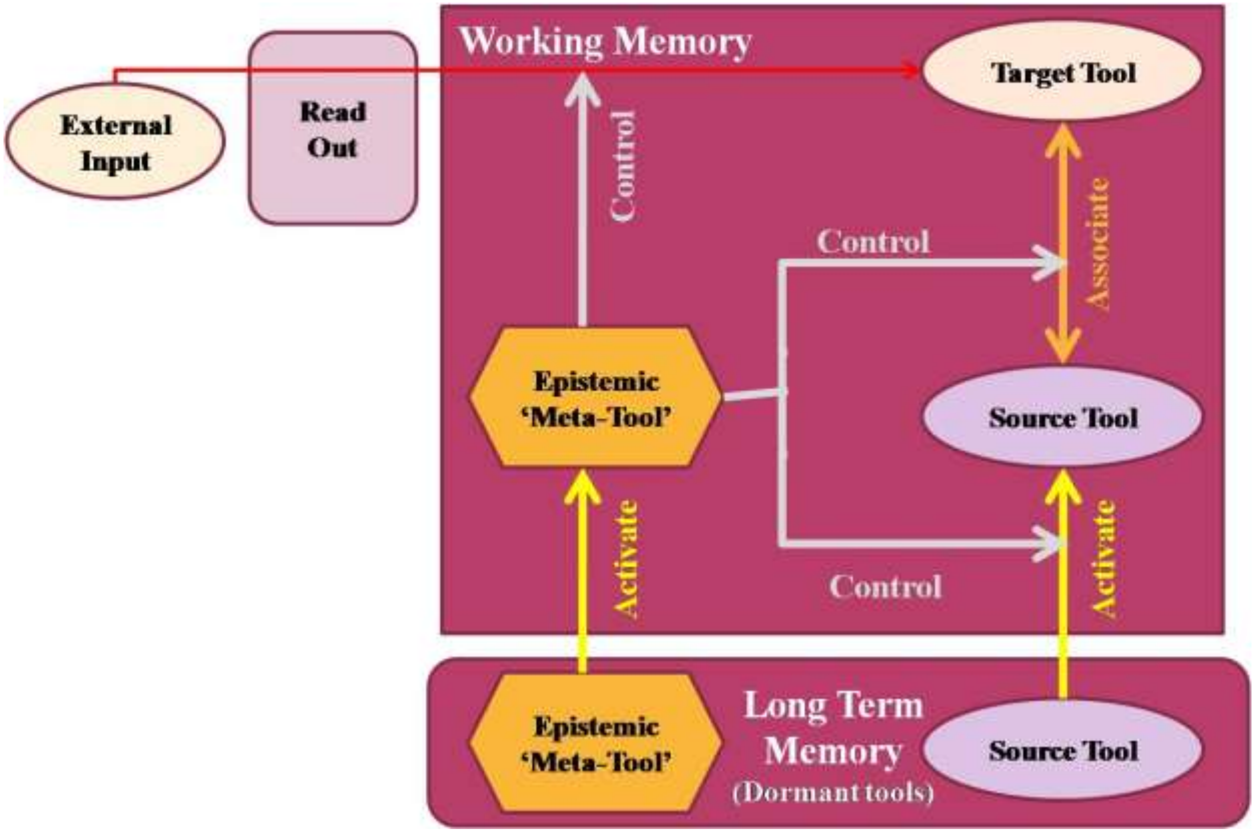


**Figure 2.10 Rebello *et al.*'s model of dynamic transfer.**

### *2.5.2.4 Schwartz's View of Dynamic Transfer and Innovation*

Schwartz *et al.* (2008) have described two kinds of transfer, similarity transfer and dynamic transfer. Similarity transfer occurs when a person applies well-formed prior knowledge to a new situation and requires that the person recognizes the two situations are similar. A failure of similarity transfer occurs in the case of "inert knowledge," when a person has the appropriate knowledge but does not spontaneously apply it. In similarity transfer, the role of the context is to cue retrieval of intact prior knowledge. This type of transfer is similar to traditional transfer.

On the other hand, dynamic transfer takes a contemporary view of transfer of learning. In dynamic transfer, "the context helps people coordinate component abilities to create a novel concept" (pg. 479). To achieve dynamic transfer the student must realize that certain skills or ideas will be useful in the learning situation. The role of the context is to coordinate different components of prior knowledge through interaction with the environment. Through the idea of dynamic transfer, Schwartz tries to explain how prior knowledge can create concepts that did not previously exist. This shift to explaining how new knowledge is built from prior knowledge mirrors Hammer's shift from studying misconceptions to conceptual resources.

See Figure 2.11 for a visual representation of similarity and Figure 2.12 for dynamic transfer. In similarity transfer, the learner recognizes that a bit of well-formed prior knowledge fits in the transfer situation. On the other hand, in dynamic transfer, the learner coordinates component ideas and skills into a new concept through interaction with the environment.

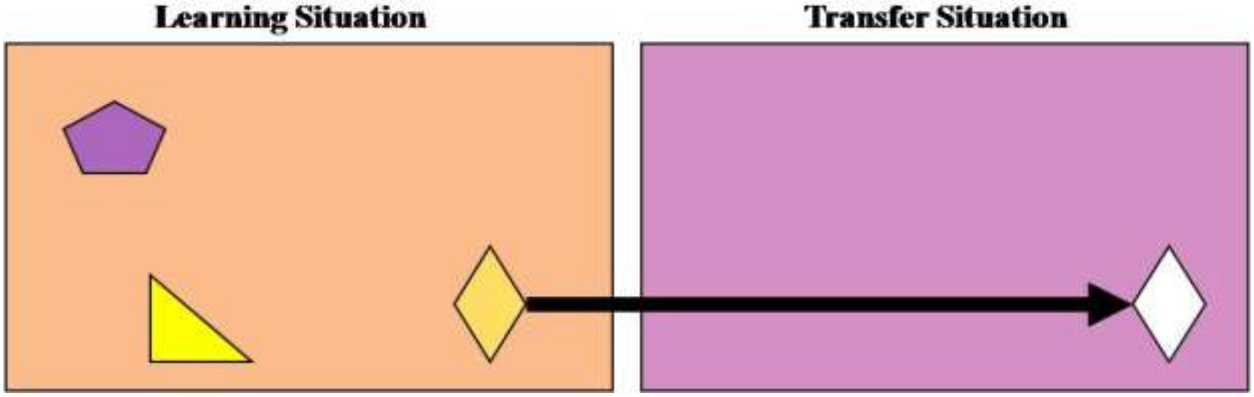


**Figure 2.11 A visual representation of Schwartz's similarity transfer.**

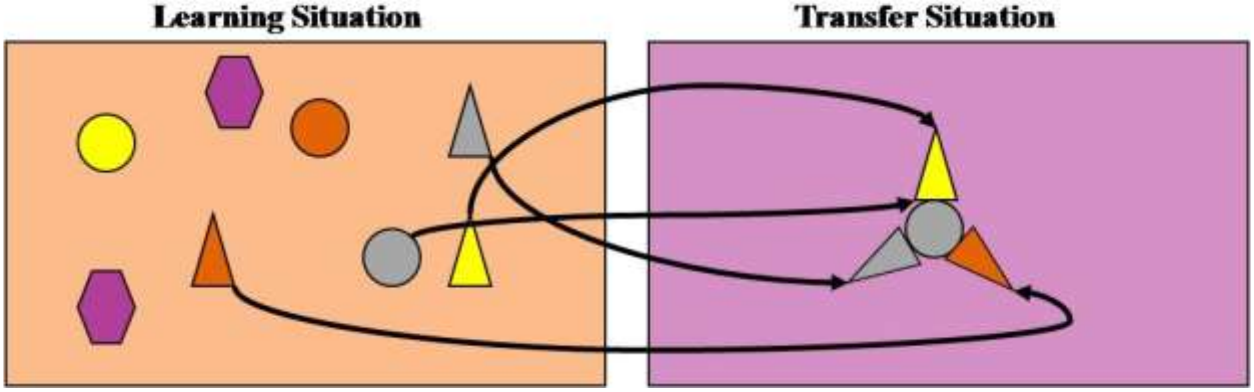


**Figure 2.12 A visual representation of Schwartz's dynamic transfer.**

Schwartz *et al.* (2008) have discussed the characteristics of an environment supportive of dynamic transfer. Their four main characteristics are that the environment allow for distributed memory, offer alternative interpretations and feedback, provide candidate structures, and act as a focal point for coordination. These characteristics are discussed below.

An environment supportive of dynamic transfer will allow individuals to distribute some of their mental work onto the environment. This distribution is necessary due to our limited working memory. The environment can assist the distribution of mental work by storing intermediate structures of ideas or concepts in two kinds of ways. First, the environment can provide the opportunities to store intermediate products of a learner's work. Schwartz offers Goel's (1995) example of architects making sketches to help come up with a new design. The sketches encapsulate the architects' intermediate ideas about their design thereby relieving the mental burden of remembering these designs. Second, the environment can have affordances and constraints that encapsulate rules thereby making it unnecessary for the learner to memorize these rules. For example, Schwartz describes Zhang and Norman's (1994) study of the Tower of Hanoi puzzle. The original puzzle involves verbal rules for moving stacks of disks, such as a larger disk cannot be placed on a smaller disk. Zhang and Norman built this verbal rule into the environment by replacing the disks with cups. This meant the participants did not have to remember the verbal rule in their minds, since the environment enforced it because the cups must fit together. They found participants were more successful in the cup task than the disk task. Thus, if we can allow students to distribute their memory onto the environment, we can expect more instances of dynamic transfer.

Another characteristic of an environment supportive of dynamic transfer is that it offers alternative interpretations and feedback. If a student has a misconception, the misconception can negatively affect his interpretation of new events. Schwartz offers an example from Bruner and Potter (1964). Brunner and Potter showed participants photos of common objects; the photos started out blurry and gradually became clearer. They found that when the pictures started out blurrier, participants need higher level of focus before they could recognize the object. This resulted suggested that participants' initial misconceptions about the image interfered with the creation of an accurate conception of the image. This means that in order to support dynamic transfer, the environment must help students overcome their initial misconceptions by providing alternative interpretations and offering feedback.

According to Schwartz *et al*. (2008), an environment supportive of dynamic transfer will also offer candidate structures by constraining and structuring possible actions. A candidate structure can be thought of as a possible framework for coordination of information. Schwartz *et al*. point out that this characteristic is similar to the idea of scaffolding. Both share the common idea that “people can learn from interacting with complex, well-structured environments” (pg. 493). In a 2005 study with school age children, Schwartz, Martin and Pfaffman (2005) found students were able to use the candidate structures of mathematics, such as multiplication, to coordinate weight and distance in balancing problems. The students were able to recognize multiplication as a possible framework for combining the weight and distance in the balancing problems. Ideally, by providing students with scaffolding, they will internalize the new structure and be able to perform the task without the scaffolding present.

The final characteristic of an environment supportive of dynamic transfer is that it should allow the student to bring together different pockets of knowledge and serve as a focal point of coordination of this knowledge. A focal point for coordination can be thought of as the aspect of the environment that allows students to combine ideas. Schwartz *et al*. (2008) offer the example of a board gamed designed by Griffin, Case, and Siegler (1994), which was used to teach young children about numbers. The game requires the children to count spaces, pick up chips, and decide if they have more or fewer chips than the other players. Thus, the game helps the student coordinate the ordinal (first step, second step) and cardinal (one step, two steps) conceptions of number. An environment supportive of dynamic transfer should help students bring together different pieces of knowledge that they would not have necessarily coordinated on their own. Table 2.3 below provides a summary of these characteristics.

**Table 2.3 Schwartz's (2008) Characteristics of an Environment that Supports Dynamic Transfer**

| Characteristic | Description | Example |
|---|---|---|
| Allows for distributed memory | Provide opportunities to store intermediate products of work; Use constraints to encapsulate rules | Artists' sketches |
| Offers alternative interpretations and feedback | Help students recognize and overcome initial misconceptions | Harder to identify a picture when it starts out blurrier |
| Provides candidate structures | Provide a framework for coordinating information | Offer multiplication as a way to coordinate distance and weight in balance problems |
| Acts as a focal point for coordination | Help combine ideas | Board game to help students think about both ordinal and cardinal conceptions of numbers |

It is interesting to investigate the idea of dynamic transfer in these studies because the physical and virtual learning environments may provide different levels of support for dynamic transfer. The characteristics of an environment that supports dynamic transfer, discussed above, provide a lens through which to compare the physical and virtual learning environments. If the physical and virtual environments result in differences in student learning outcomes, it is possible this difference results from offering different support for dynamic transfer. In the Section 2.6.3 below, the characteristics of an environment that supports dynamic transfer are compared to the properties of successful use of computers in learning science identified in the physics education research literature.

## 2.6 Literature Related to Learning with Physical and Virtual Manipulatives

In this section, I summarize some of the aspects of supporting students' learning with physical and virtual manipulatives that have already been discussed in the literature. I begin by exploring the dimension of hands-on learning and describing some of the advantages and disadvantages of learning with physical equipment and simulations. I also review the educational standards' suggestions for the use of computers in science teaching. Finally, I summarize the properties of successful computer use that have been identified in the physics education research literature and describe how these properties align with the characteristics of an environment supportive of dynamic transfer, described above. A review of previous studies in the context of physics follows in the next section.

### *2.6.1 Hands-on Learning*

What hands-on learning entails and what benefits it brings for science learning have been debated for over a century (Klahr, Triona and Williams, 2007). While hands-on science typically involves students handling physical equipment, its interpretation can vary from a general approach to instruction to a specific type of activity that can be consistent with various educational philosophies (Flick, 1993 in Klahr, Triona and Williams, 2007). In these studies, I am focusing on hands-on learning in the second sense, concentrating on a specific type of activity.

Klahr, Triona and Williams (2007) point out that even when focusing on this specific definition of hands-on learning, there still remain differences between various hands-on activities. They propose three dimensions along which it is useful to classify hands-on activities to alleviate the confusion associated with the term. The first dimension describes whether the activity uses physical or virtual materials. The second dimension describes the nature of the knowledge being learned from domain-general knowledge to domain-specific knowledge. Domain-general knowledge includes process skills, such as the relationship between theory and evidence, while domain-specific knowledge refers to specific content, such as the physics definition of work. The final dimension describes the instructional context, from discovery learning, where little instruction is given, to direct instruction. See Figure 2.13 for a visual representation of these dimensions.

In this study, I held domain-specific knowledge constant, as students will be learning about physics principles in relation to simple machines. Additionally, I held the instructional context constant, towards the discovery-learning end of the dimension. I varied whether the students use physical or virtual materials to perform their activities. Referring to Figure 2.13, this is basically comparing the right and left upper-front octants. As Klahr, Triona and Williams (2007) state, assessing a study in this way helps reduce the risk of confounding the experiment.

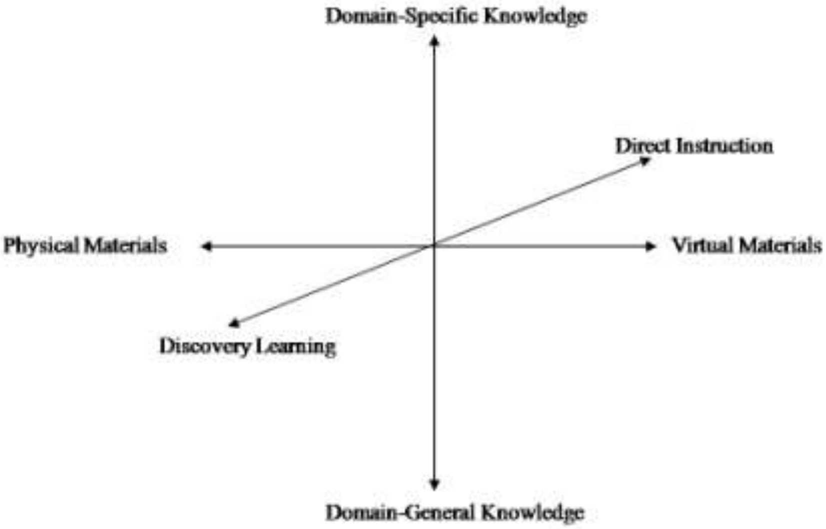


**Figure 2.13 A visual representation of Klahr, Triona and Williams (2007) dimensions of hands-on learning.**

### *2.6.1.1 Learning with Physical Manipulatives*

Triona, Klahr and Williams (2007) offer a useful summary of the advantages and disadvantages to using physical equipment. Activities that use physical equipment may promote learning because they are consistent with the way students' cognition develops, moving from the more concrete to the more abstract. Additionally, the kinesthetic involvement of manipulating physical materials may provide additional sources of brain activation. Finally, the intrinsic interest of these types of activities typically increases students' motivation and engagement.

However, there are also several disadvantages that may result from having students perform activities with physical materials. When students perform activities with physical materials, they may not always get the result the teacher expected. The nature of physical activities can sometimes lead to confusing or inconsistent feedback or the mapping between the behavior of the physical activities and their "textbook" representation may be inadequate. Physical materials may also allow students to perform "off-task" activities, gathering information not pertinent to the current lesson. Finally, physical materials are often expensive in terms of logistics, time and money.

For example, consider physical activities used to support student learning about pulleys, as used in this research. A potential advantage of the physical activity is that it provides a kinesthetic experience, allowing the students to feel a difference in force between different pulley systems.  However, a potential disadvantage is that friction and slip in the physical pulley systems lead to students often finding that the work needed to lift a load changes when the pulley system changes.

#### *2.6.1.2 Learning with Virtual Manipulatives*

The virtual materials considered in this study are limited to computer programs controlled by students through a mouse and keyboard.  These types of materials may offer several advantages over their analogous physical materials.  Computer programs can provide additional representations, such as a frictionless environment or the elimination of measurement error, that are not accessible with physical materials (Zacharia and Anderson, 2003).  Additionally, virtual materials can be designed to focus students' attention on formal variables, parameters and frames of reference (Sadler, Whitney, Shore and Deutsch, 1999).  Computer programs can also provide students with dynamically changing graphs related to the experiments they are simulating (Triona and Klahr, 2003).  Computer experiments tend to be less time consuming, since, for example, they require minimal set up.  Finally, computer simulations do not require specialized equipment on an experiment-by-experiment basis.  Rather, the same computer can be used to perform various activities (Thornton and Sokoloff, 1990).

However, there are also disadvantages associated with performing experiments with virtual equipment.  Performing activities in a computer simulation presents students with a decontextualized representation of a real-world phenomenon (Hofstein and Lunetta, 2004). Also, having students learn from activities with virtual materials is asking them to learn in a different way than scientists originally learned the material (Steinberg, 2000).

Students can also view things in a computer simulation that are not directly observable in the real world, such as the flow of electrons.  This may be an advantage, helping students to build models of things they cannot traditionally observe directly, such as conservation of charge. However, this may also be a disadvantage, as students are learning in a different way than scientists originally discovered the concepts.

This research investigated how the advantages and disadvantages associated with physical and virtual manipulatives manifest as students learn about the physics concepts related to simple machines.

### *2.6.2 Computers in Educational Standards*

The National Science Education Standards (NSES) describe how computers should be used in science education (1996). As part of the "Science as Inquiry" standard, students should be able to use computers to collect, analyze and display data. The "Unifying Concepts and Processes" standard states that students should understand that computer simulations are one form of scientific model that have explanatory power and can help us understand how things work. Additionally, the NSES emphasize that students need to know how knowledge in a secondary source, such as a computer simulation, is acquired and understand the level of authority and acceptance of that source within the scientific community.

The National Science Teachers Association (NSTA) has stated its views on the use of computers in science education in the position statement "The Use of Computers in Science Education" (1999). The NSTA recognizes that computer simulations provide a valuable resource for learning scientific concepts and processes but assert that computers should be used to enhance and not to replace essential "hands-on" laboratory activities. For example, the NSTA suggests computer simulations should be used in cases when an experiment requires expensive, hazardous or unavailable materials, levels of skill not yet achieved by students, or more time than is possible or appropriate.

### *2.6.3 Properties of Successful Computer Use*

In reviewing the relevant literature I have built a "master list" of the reasons computers can serve as effective learning tools. Thornton and Sokoloff (1990) successfully used microcomputer based labs (MBLs) in a kinematics curriculum. They suggested five important characteristics of the MBLs: students focused on the physical world, immediate feedback was available, collaboration was encouraged, tools were used to reduce drudgery, and students moved from the specific and familiar to the more general and abstract. Redish, Saul and Steinberg (1997) successfully used MBLs in the context of velocity and Newton's Third Law. They agreed with Thornton and Sokoloff's list of characteristics, and added the conjecture that students were actively involved in exploring and constructing their own understanding. Finally, Finkelstein *et al*. (2005) successfully used a simulation to replace a physical electrical circuits lab. They noted that the simulation was successful because it made visible models that were useful for forming concepts and constrained students in productive ways. These conditions are made possible by a combination of the instructional tools, curriculum and setting.

The characteristics identified for successful simulations and dynamic transfer (described in Section 2.5.2.4) are summarized in Table 2.4 below. I find significant overlap between the properties of successful computer use and the characteristics of an environment supportive of dynamic transfer, as shown in Table 2.5. The remaining three properties for successful computer use are more general views of learning. For example, C6 relates to a constructivist view of learning. The overlap between these characteristics suggests that a successful computer simulation may also support dynamic transfer.

**Table 2.4 A Summary of the Properties of Successful Computer Use and the Characteristics of an Environment for Dynamic Transfer**

| **Properties of Successful Computer Use** | **Characteristics of Environment for Dynamic Transfer** |
|---|---|
| C1. Focus on the physical world. | DT1. Allows for distributed memory. |
| C2. Immediate feedback is available. | DT2. Offers alternative interpretations and feedback. |
| C3. Collaboration is encouraged. | DT3. Offers candidate structures by constraining and structuring actions. |
| C4. Powerful tools reduce drudgery. | DT4. Provides a focal point for coordination of different knowledge pockets. |
| C5. Understand the specific and familiar before moving to the more general and abstract. | |
| C6. Students are actively engaged in exploring and constructing their own understanding | |
| C7. Useful models for forming concepts are made visible. | |
| C8. Students are constrained in productive ways. | |

**Table 2.5 The Alignment Between Dynamic Transfer Characteristics and Computer Use Properties**

| **Dynamic Transfer Characteristic** | **Aligned Computer Use Property** |
|---|---|
| DT1 | C4 |
| DT2 | C2 |
| DT3 | C8 |
| DT4 | C5, C7 |

## 2.7 Review of Previous Studies on Physical and Virtual Manipulatives

In this section, I discuss studies that have already been conducted to investigate how student learning is supported by experimentation with physical and virtual manipulatives. As the topic of learning with physical and virtual materials is broad in terms of populations, topics and types of materials studied, I focus specifically on studies in physics that involved introductory physics students and computer simulations. For each study presented, I describe the central research question, experimental design, and findings. Most studies focus on students' conceptual understanding as measured by a pre-test and post-test design or analysis of students' written responses. However, some studies have looked at other factors, such as students' confidence, abilities to perform tasks with physical equipment, and beliefs about and attitudes towards different types of experimentation.

### *2.7.1 Steinberg (2000): Air Resistance*

Steinberg's (2000) study compared how students learned about air resistance through performing either pencil-and-paper or computer activities. The participants were enrolled in their first semester of introductory calculus-based physics. One group of students used a computer program that allowed them to vary experimental parameters and displayed the ball's motion and graphs of position versus time and velocity versus time. Another group of students performed pencil-and-paper activities, which did not include any physical manipulatives.

In both conditions, the students began by drawing free body diagrams and kinematics graphs for a ball without air resistance. In the pencil-and-paper condition, students then compared the accelerations of the ball at several points and had to resolve this comparison with their prediction graphs and diagrams. In the simulation condition, students ran the simulation with no air resistance and compared their graphs with the computer-generated graphs.

Next, in both conditions, the students considered a ball thrown vertically with air resistance present. They discussed real world experiences with air resistance and three possible models of resistive forces. In the pencil-and-paper condition, students drew free-body diagrams and graphs depicting their predictions of how the ball would behave when thrown vertically with air resistance present. In this condition, students had to resolve their understanding of the ball's motion by using Newton's Second Law. They were provided with an explicit discussion of terminal velocity. In the simulation condition, after discussing the three possible models, students used the simulation to display the motion and kinematics graphs for a ball thrown vertically with a resistive force proportional to the square of its velocity. Students then compared this motion to the motion with no air resistance and discussed specific features, such as terminal velocity.

Students' learning in the two conditions was assessed by exam performance and classroom observations. A question related to the students' understanding of air resistance was included on the second midterm exam. It required students to figure out the effect of air resistance in a new context, choose the correct graph for the motion, compare the effect of air resistance with that of friction and solve a qualitative problem. Steinberg found no significant difference between the performances of students in the pencil-and-paper or simulation conditions. However, based on classroom observations, Steinberg issued a warning about the use of computer simulations. He suggested students could misuse the computer by quickly accepting the computer's answer as correct rather than trying to build or justify the answers for themselves. He linked this behavior to the computer encouraging an "authoritarian" view of learning. In the language of the resources approach to epistemology described above, this would be an example of the presence of the computer activating the resources related to knowledge coming from authority, such as knowledge is propagated and gained through accumulation, as opposed to resources related to knowledge being inferred or developed from other knowledge.

### *2.7.2 Klahr, Triona and Williams (2007): Mousetrap Cars*

Klahr, Triona and Willaims' (2007) study focused on how seventh and eighth grade students used physical and virtual manipulatives to learn how to make a mousetrap car travel the furthest distance. A mousetrap car uses an ordinary mousetrap to propel a small car and can travel dozens of feet; a mousetrap car experience is a useful context for learning about conservation of energy, torque, friction and mechanical advantage. Their study focused specifically on the initial stages of such an experiment, where the students were trying to determine which features of the car caused which effects.

Students in the physical condition worked with physical cars, selected their components, and ran the car to see the distance it traveled. Students in the virtual condition used a simulation that allowed them to use a computer mouse to select components, assemble cars, and run them. In the simulation, the cars are depicted in two-dimensional cartoon-like drawings rather than photographs or videos. The researchers created four conditions by also specifying whether each group of student could test a fixed number of cars or test cars for a fixed amount of time. In the fixed number of cars condition, students were given as much time as they needed to build and test six cars. In the fixed amount of time condition, students had 20 minutes to build and test as many cars as they could; this condition allowed for the possibility that students in the virtual condition could test more cars since their cars would take less time to construct.

Students' learning was assessed with a pre- and post-test. The tests included multiple-choice questions about how each component would affect the distance traveled by the mousetrap car and asked students to rate their confidence in each answer they chose. During the pre-test students were also asked if they had previous experience with mousetrap cars, while during the post-test students were asked if any other factors not covered in the test would affect the distance traveled by the car. The researchers found no significant difference between the four conditions in either the students' performance on the test or their confidence in their answers. The researchers also analyzed this data by gender and found that while there was no significant difference in performance between girls and boys, girls were significantly less confident in their answers than were boys on both the pre-test and the post-test. This difference in confidence was not affected by whether the student had performed physical or virtual experiments. Additionally, the "best" car designed by each group was able to travel roughly the same distance, indicating the conditions offered comparable support for the design of an optimal car.

Based on their findings, Klahr, Triona and Williams suggest that since they did not uncover a difference in learning or confidence, other factors related to physical and virtual manipulatives should be the basis for choosing which to use. The researchers point out that virtual manipulatives are generally easier to develop, implement and manage than physical manipulatives. In addition, virtual experiments take less time, space and effort and are easy to duplicate. Thus, in some cases, virtual experiments seem to offer more advantages than physical experiments.

### *2.7.3 Finkelstein (2005): Circuits*

Finkelstein *et al*.'s (2005) study investigated how students enrolled in second-semester introductory algebra-based physics learned about electrical circuits from a laboratory that used either physical equipment or a computer simulation. Students in the simulation condition used the Circuit Construction Kit (CCK), which was designed as part of the Physics Education Technology (PhET) project.  The CCK allows students to manipulate resistors, light bulbs, wires and batteries, which have user-adjustable parameters, such as resistance or voltage.  The batteries and wires can be run with or without resistance, allowing students to see both ideal and real behavior.  The CCK also includes a simulated voltmeter and ammeter and displays moving electrons to show current flow and conservation.  The researchers also included a third group of students enrolled in a calculus-based introductory physics course as a control; these students had also learned about circuits in lecture, but had not had any laboratory experience.

Students in both the physical and simulation conditions completed a pre-laboratory activity, with three identical questions and one question that varied with condition.  On the question that varied, students in the physical condition drew a circuit they thought could light a bulb using a battery and single wire, while students in the simulation condition built the same circuit with the CCK.  The students in both conditions performed the same activities, including examining resistors in series and parallel, building simple circuits, predicting the behavior of circuit elements, and developing a method to measure resistance with either physical circuit equipment or the CCK.  At the end of the lab, students in both conditions were given the challenge task to build a circuit using physical equipment and to describe and explain the circuit's behavior when broken at a certain spot.  Students in the control group performed the same challenge task.

The researchers compared the conditions based on the time needed to complete the challenge task, the challenge task responses, and performance on several questions on the final exam.  While students in the simulation condition had no prior experience with physical equipment, they still completed the challenge circuit in a statistically significantly shorter time than the students in the physical condition.  Students in the simulation condition took, on average, 14.0 minutes to complete the challenge circuit compared to 17.7 minutes for students in the physical condition.  Students in the control group took the longest, an average of 26.7 minutes, to complete the challenge.  The researchers graded students' challenge circuit explanations on a rubric and found a statistically significant difference in favor of students in the simulation condition.  Three questions related to the challenge circuit were included on the final exam; students were asked to explain the behavior of current and voltage in a circuit with series and parallel components.  While the researchers found no significant difference in performance on questions not related to circuits, they did find a significant difference in performance on circuit questions, in favor of students in the simulation condition.

The researchers also noticed several trends from their classroom observations. Observers noted that students' "messing about" in the simulation condition was generally limited to building circuits. While students in the physical condition also "messed about" making circuits, they were sometimes distracted by off-task activities, like making bracelets out of wires. Both wire color and the observation of a dim bulb in a bright room caused problems for students in the physical condition. The teaching assistants in the simulation condition were observed to be freer to answer students' questions as opposed to the teaching assistants in the physical condition who spent their time getting equipment and troubleshooting problems, such as failure to see a dim bulb as lit. However, one section of the simulation condition did experience repeated computer failures.

Based on these findings, Finkelstein *et al*. suggest "that it is possible, and in the right conditions preferable, to substitute virtual equipment for real laboratory equipment" (pg. 6). They urge that this not be taken as a recommendation to replace all circuit labs with a simulation but rather emphasize that these results challenge the conventional wisdom that students always learn more from performing an experiment with physical equipment.

### *2.7.4 Zacharia Studies*

Zacharia, along with other researchers, has conducted several studies to investigate how physical and virtual materials support students' learning. These studies cover many physics topics, including mechanics, waves and optics, thermal physics and electric circuits. His studies' participants were future or in-service physics teachers enrolled in conceptual-based introductory physics courses. Zacharia began by investigating the usefulness of simulations as pre-laboratory activities, but moved toward studies to investigate the effects of physical and virtual experimentation on student learning.

In an early study, Zacharia (2003) investigated the effects of computer simulations and experiments with physical equipment on future physics teachers' ideas about these types of activities. He studied their beliefs about and attitudes towards those activities and using them in their own classrooms, their attitudes towards physics, whether their beliefs affected their attitudes, and whether their attitudes affected their intentions. Before the laboratory, all students completed a reading assignment and a problem set related to the laboratory. Then, students in the physical condition solved additional problems and compared their solutions to a solution key, while students in the simulation condition made a prediction about the effect of changing certain parameters in the simulation, observed the effects of the those changes, and reconciled the differences between their prediction and observation. Throughout the semester, each student was assigned to perform the experiments in a random order of simulation and no-simulation conditions. The physics topics studied include mechanics, waves and optics, and thermal physics. Using a pre-post comparison study and the Theory of Reasoned Action, Zacharia found that the students' beliefs about the activities affected their attitudes towards the activities and their attitudes affected their intentions about using the activities in their own classrooms. Before the study, the students' expressed the belief that inquiry-based experiments with physical equipment were the most beneficial, but after the study they believed a combination of simulations with physical experiments would be more beneficial.

In a second study, Zacharia and Anderson (2003) and Zacharia (2005) used the same context to study how the pre-laboratory activities affected students' conceptual understanding and their abilities to make correct predictions before performing experiments and their conceptual understanding. Students who used the simulation prior to the laboratory were found to make more scientifically correct predictions and better quality explanations about the phenomena in the experiments. Zacharia and Anderson (2003) tested the students before any activities, after the pre-laboratory activity, and again after the laboratory experiment. Students in the simulation condition were found to have greater conceptual change after the pre-laboratory activity, while students in the no-simulation condition showed no conceptual change. The simulation paired with the laboratory experiment also resulted in greater conceptual change than the extra problem set paired with the experiment. Zacharia (2005) analyzed students' explanations based on their scientific accuracy, depth and formality (everyday, descriptive, causal or formal). Students in both conditions started with mostly descriptive or everyday explanations; but while the explanations of students in the no-simulation condition remained descriptive and everyday, those of students in the simulation condition transitioned to mainly formal and causal explanations. As before, the simulation condition was found to promote more scientifically accurate and also deeper explanations.

In more recent studies, Zacharia has turned to studying the effects on student learning of experimenting with physical equipment, virtual equipment, and both types of equipment. Zacharia (2007) compared how students' understanding of electric circuits was supported by either physical experiments or some physical and some virtual experiments. Students in the all-physical condition performed three sets of activities with physical manipulatives, while students in the physical-plus-simulation condition performed two sets of activities with physical manipulatives and one set with virtual manipulatives. Students were tested before and after the sequence began with an electric circuits test, as well as before and after each part of the curriculum with curriculum specific questions. While both types of experimentation led to gains from the electric circuits pre-test to post-test, the researchers found a statistically significant different in post-test scores, in favor of students in the physical-plus-simulation condition. This finding suggests that the combination of virtual and physical experimentation was more beneficial than physical experimentation alone.

In the third part of the curriculum, one group of students used physical manipulatives and the other group used a computer simulation; thus, the third curriculum test assessed the affects of physical and virtual experimentation on students' understanding of this particular set of topics. A phenomenographic analysis revealed that on both the pre-test and post-test students in the two conditions had the same categories of conceptions about, or ways of describing, how voltage was measured. On the pre-test, the two conditions also had the same prevalence of categories, but on the post-test students in the simulation condition had a higher prevalence of scientifically correct categories. Similar to the electric circuits tests, while both conditions showed an improvement from pre-test to post-test, the physical-plus-simulation condition had significantly higher post-test scores, suggesting virtual experimentation was more beneficial than physical experimentation. Zacharia (2007) later suggested the observed performance difference may be a result of the faster manipulation allowed by the simulation. Due to the faster manipulation, students using the simulation could repeat and perform more experiments and devote more time to conceptual aspects.

Zacharia, Olympiou and Papaevripidou (2008) further investigated the findings of Zacharia (2007) and Zacharia (2005) in a different domain, specifically heat and temperature. Students were again broken into groups that performed physical only or physical and virtual experiments. The virtual manipulatives were similar to the physical manipulatives, except again the virtual manipulatives allowed for faster manipulation.  This study confirmed the results of the Zacharia (2007) and Zacharia (2005) studies, again finding students who used the simulation had higher post-test scores and a higher prevalence of scientifically correct conceptions and providing support for the idea that the source of this difference may be the speed of manipulation.

Zacharia and Constantinou (2008) sought to control for the speed of manipulation of the physical and virtual manipulatives.  The researchers again chose to study the domain of heat and temperature.  In this study, however, students performed only one type of experiment, either physical or virtual.  The simulation allowed students to perform experiments on a virtual workbench by clicking on icons and moving objects and materials to their desired position.  For example, water is heated by placing a beaker of water on a heater and frozen by putting the beaker in the refrigerator.  Time, temperature, volume and other information are displayed.  To control for the time on task, students in the physical condition were supplied prepared materials, such as preheated water.

Students were again assessed by pre-tests and post-tests that were analyzed quantitatively by score and qualitatively by categories of conceptions.  Post-test scores were statistically significantly higher than pre-test scores for students in both conditions.  In this study, however, there was no significant difference between students in the two conditions, suggesting the physical and virtual manipulatives were equally successful in promoting students learning.  Also, students in the two conditions shared the same categories of conceptions both before and after performing the experiments.  Both conditions had similar shifts in frequency from non-scientifically correct to scientifically correct conceptions and shared the same most frequent non-scientifically correct conception.  Thus, with the speed of manipulation controlled, physical and virtual experimentation were equally effective at promoting students’ learning about heat and temperature.

Zacharia and Constantinou (2008) state “this finding challenges commonly held assumptions about laboratory work in the physics classroom and calls for a redefinition and restructuring of experimentation to include both physical and virtual manipulatives” (pg 428).  In order to answer this call, further research is necessary to understand how physical and virtual manipulation can best be integrated in physics learning.

### *2.7.5 Summary of Previous Studies on Physical and Virtual Manipulatives*

Table 2.6 presents a summary of the studies presented in this section for easier comparison of context and results. While some studies have found a difference in student learning when supported with physical or virtual manipulatives, others have not. From the studies discussed here, it seems the specific physics topic students are to learn does not predict whether their learning will be better supported by physical or virtual experimentation. When the speed of manipulation was controlled, as in Klahr, Triona and Willaims (2007) and Zacharia and Constantinou (2008), virtual and physical manipulation were found to offer equivalent support for student learning. Thus, there is no clear-cut answer available in the current literature as to whether to use physical or virtual manipulatives.

This disparity suggests the need for further research. Specifically, the difference in findings between Zacharia, Olympiou & Papaevripidou (2008) and Zacharia and Constantinou (2008) highlights the importance of controlling all aspects of the curriculum except the mode (physical or virtual) of experimentation. This includes controlling the curriculum along the three dimensions described by Klahr, Triona and Willaims (2007) and summarized above. Expanding this idea, it is important to be explicit about the advantages offered by the physical and virtual manipulatives used in a specific study.

Zacharia and Constantinou (2008) have stated, “It is essential to expand the empirical base through similar research to test further these perspectives as well as to ground theoretical conjectures regarding a framework for integrating physical and virtual manipulatives within physics learning environments” (pg. 428). Klahr, Triona and Willaims (2007) have stated, “Clearly, a large space of experimental designs remains to be explored in order to fully understand the nuances of hands-on science instruction and to further its optimal use” (pg.199). In these studies, I contribute to the current body of literature by expanding the topics studied, using innovative experimental designs, and investigating additional factors that could affect student learning.

**Table 2.6 A Summary of the Reported Studies**

| **Study** | **Context** | **Conditions** | **Findings** |
|---|---|---|---|
| Steinberg (2000) | Air resistance | Pencil-and-paper/ Simulation | • No difference in performance on exam question<br>• Computer may encourage authoritarian view of learning |
| Klahr, Triona | Mousetrap car | Physical/Virtual; | • No difference in conceptual |

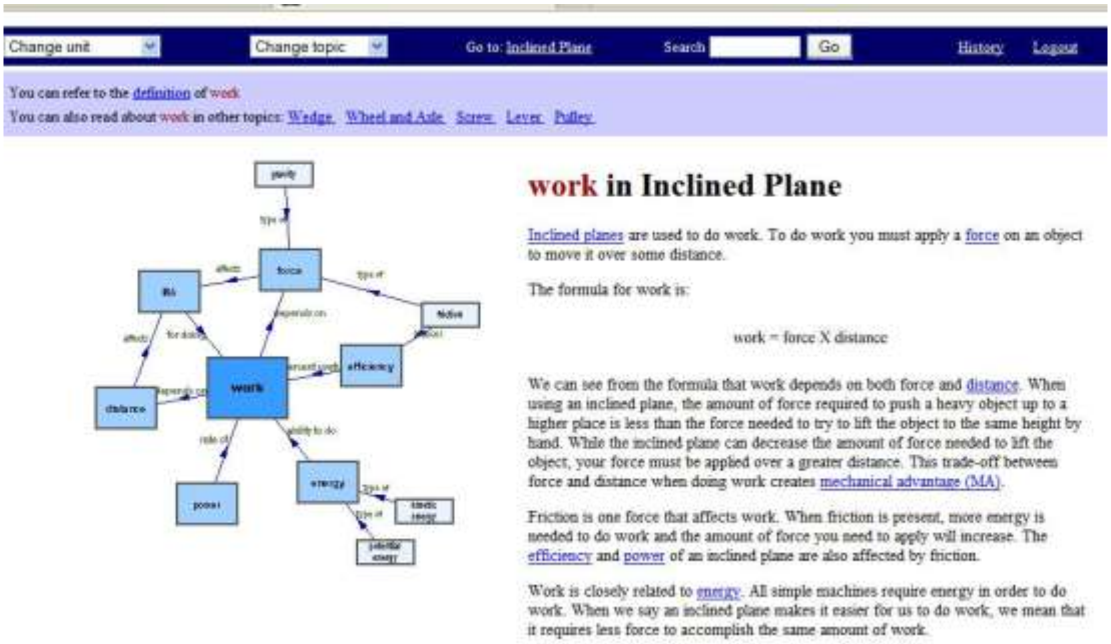
| **Study** | **Context** | **Conditions** | **Findings** |
|---|---|---|---|
| and Willaims (2007) | design | Fixed number of cars/Fixed time | change about causal factors<br>- No difference in ability to design cars<br>- No difference in confidence in knowledge |
| Finkelstein et al. (2005) | Circuits | Physical/Virtual | Students in virtual condition:<br>- Built a physical circuit quicker<br>- Had better written explanations of circuit behavior<br>- Performed better on related exam question |
| Zacharia (2003) | Mechanics; Waves & Optics; Thermal Physics. | Prelaboratory assignment: Textbook problems/ Simulation | - Using simulations improved students beliefs and attitudes about simulations<br>- Students became more likely to use simulations in their own classrooms |
| Zacharia and Anderson (2003) | Same as above | Same as above | Students who used simulation:<br>- Made more scientifically correct predictions<br>- Provided more scientifically correct explanations<br>- Had greater conceptual change |
| Zacharia (2005) | Same as above | Same as above | Students who used simulation:<br>- Provided more formal explanations<br>- Provided more scientifically correct explanations |
| Zacharia (2007) | Circuits | All physical experiments/ Some physical, some virtual experiments | Students who performed virtual experiments<br>- Had higher post-test scores<br>- Had higher prevalence of scientifically correct conceptions |
| Zacharia, Olympiou & Papaevripidou (2008) | Heat & Temperature; time on task not controlled | Same as above | Same as above |
| Zacharia and Constantinou (2008) | Heat & Temperature; time on task controlled | Physical/Virtual | - No difference in post-test scores<br>- No difference in prevalence of conceptions |

## 2.8 The CoMPASS Curriculum

This study made use of the CoMPASS (Concept-Mapped Project-based Activity Scaffolding System) curriculum. The CoMPASS curriculum combines physical and virtual experimentation with an online hypertext system, shown below. Each mode of learning has its own advantages. As discussed in more detail ealier, physical experimentation engages students in the use of physical equipment, while virtual experimentation provides easy control of parameters and additional representations of data. Investigations in the online hypertext system provide students with the accepted scientific language to explain their experience and understand theories. The CoMPASS curriculum is broadly based on the principle of Learning by Design$^{TM}$ (Kolodner *et al*., 2003). Below, I describe the hypertext system and previous studies involving the CoMPASS curriculum. As the physical and virtual manipulatives changed throughout the studies, I describe those in a later section. I also include a brief section on the ideas of Learning by Design$^{TM}$.

### *2.8.1 The CoMPASS Hypertext System*

The CoMPASS hypertext system, pictured below in Figure 2.14, differs from a textbook in that it does not present information in a linear manner. Instead, it allows students to choose their own path through the information, bringing inquiry into reading as students explore their own questions. Students navigate through the system either by clicking on concepts in the concept map or clicking on links in the text. Also, the CoMPASS hypertext system is designed to allow students to see the same concept from multiple views. For instance, a student reading about “work” in the context of pulleys can in one mouse click switch to reading about “work” in inclined planes. These affordances are only useful if students understand the structure of the system well enough to make good navigational choices (Puntambekar, Stylianou and Hübscher, 2003).



You can refer to the definition of work

You can also read about work in other topics: Wedge Wheel and Axle Screw Lever Pulley

work in Inclined Plane

Inclined planes are used to do work. To do work you must apply a force on an object to move it over some distance.

The formula for work is:

work = force X distance

We can see from the formula that work depends on both force and distance. When using an inclined plane, the amount of force required to push a heavy object up to a higher place is less than the force needed to try to lift the object to the same height by hand. While the inclined plane can decrease the amount of force needed to lift the object, your force must be applied over a greater distance. This trade-off between force and distance when doing work creates mechanical advantage (MA).

Friction is one force that affects work. When friction is present, more energy is needed to do work and the amount of force you need to apply will increase. The efficiency and power of an inclined plane are also affected by friction.

Work is closely related to energy. All simple machines require energy in order to do work. When we say an inclined plane makes it easier for us to do work, we mean that it requires less force to accomplish the same amount of work.

**Figure 2.14 A screenshot of the CoMPASS hypertext system.**

In the design of the hypertext system, relational concepts maps were chosen (Puntambekar, Stylianou and Hübscher, 2003). In a hierarchical concept map, a definite parent-child relationship exists between nodes. On the other hand, a relational concept map has many links between nodes, representing the connections between concepts (Shavelson, Lang and Lewin, 1994). See Figures 2.15 and 2.16 for a visual representation of the difference between hierarchical and relational concept maps. Additionally, a fish-eye view was chosen to fit the maps on the screen. In the fish-eye view, the selected concept becomes the focus and is maximized while the other concepts are minimized, as shown in Figure 2.17 above (Furnas and Bederson, 1995). Concepts more closely related to the selected concept are larger and appear closer to the focus.

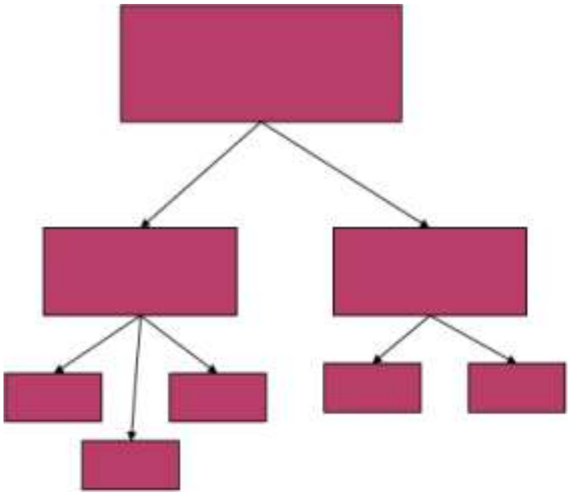


**Figure 2.15 A visual representation of a hierarchical concept map.**

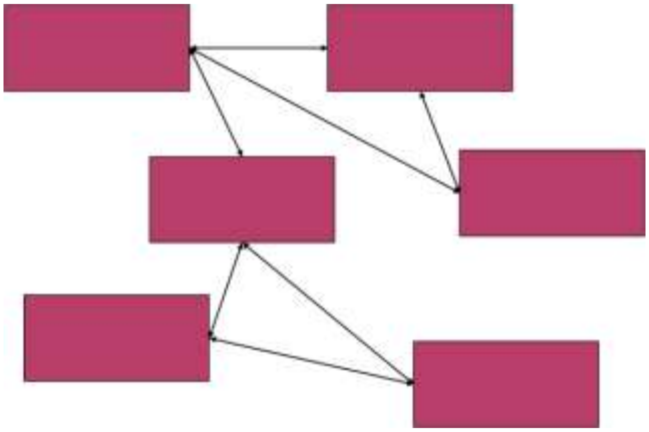


**Figure 2.16 A visual representation of a relational concept map.**

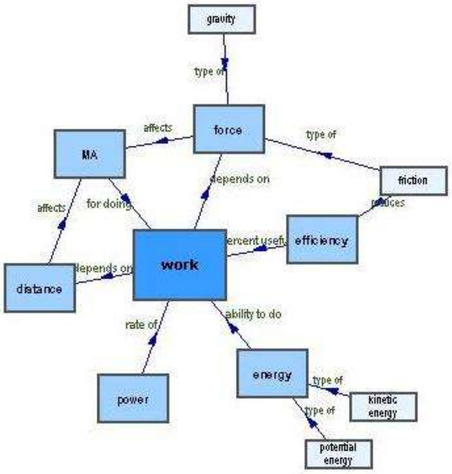


**Figure 2.17 A screenshot of the fisheye view used in CoMPASS.**

Logfiles are used to keep track of students' actions in the hypertext system (Puntambekar, Stylianou and Hübscher, 2003). The logfiles record the topics and concepts students visited, the order in which the concepts were visited, the time spent on each concept, and the source of navigation (text or map). The logfiles can then be analyzed using Pathfinder Analysis (Schvaneveldt, 1990) to reveal students' navigation patterns. The Pathfinder Analysis involves converting the logfile data to a "proximity matrix" showing nodes and transitions. A graphic is then created showing which concepts students visited most often and how they navigated between them. A clustering algorithm then groups similar navigation patterns. Figures 2.18 and 2.19 below depict example Pathfinder graphics. Each node represents a concept and each line represents a transition from one concept to another; the line thickness indicates the frequency of a particular transition. In the Figure 2.18, the student made most of his navigation transitions from the same concept (the main topic, inclined planes). However, in Figure 2.19 the student made transitions between many different concepts.

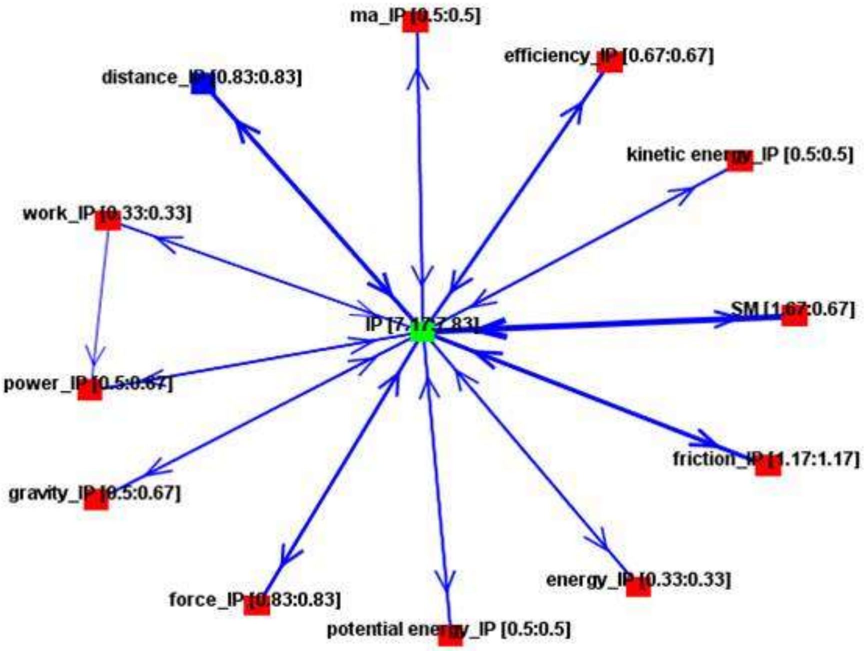


**Figure 2.18 Example Pathfinder graphic: transitions from one topic.**

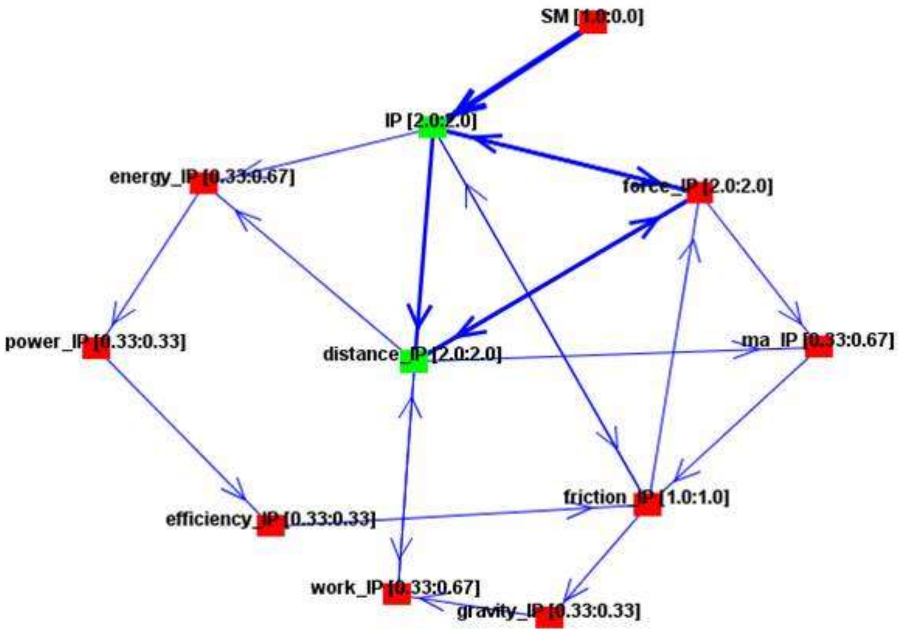


**Figure 2.19 Example Pathfinder graphic: transitions from many topics.**

### *2.8.2 Previous Studies on the CoMPASS Curriculum*

In a previous study on the CoMPASS hypertext system, researchers investigated whether the concept map was more useful as a navigational aid than an index (Puntambekar, Stylianou and Hübscher, 2003). They compared pre-test and post-test scores, concept map scores, and navigation patterns for middle school students who used either the index or the concept maps as navigational aids. Students who used the maps were found to have more focused navigation, while students who used the index tended to navigate alphabetically. Specifically, students who used the maps visited more concepts related to the instructional goal and spent more time on those concepts. No difference was observed in the students' factual knowledge, but students who used the maps showed greater depth of knowledge.

CoMPASS researchers also investigated the types of navigational support students needed in order to use the hypertext system successfully (Puntambekar and Stylianou, 2005). Pathfinder analysis was used to group the navigational patterns of 74 middle school students. Clusters differed on the richness and focus of investigation and whether students visited concepts within (i.e. only read about concepts in inclined planes) or across topics (i.e. read about the same concept in pulleys and inclined planes). These results suggested students needed support to (1) reflect on their goals to make decisions about which topics to visit, (2) integrate information about different concepts and monitor understanding of concepts, (3) understand the representation of information, and (4) visit concepts across different topics. Students who received this kind of support performed significantly better on a concept map test, which measured students' explanations for the concepts included in their map and the connections between those concepts. These studies have informed the design of the version of the CoMPASS hypertext system that is used in this research.

In another study, an eight-week implementation of the CoMPASS materials for simple machines was studied in 7th grade classrooms (Leonard and Rebello, 2007). Researchers focused specifically on students' conceptions of "force" and "work." In CoMPASS, force is called "effort force" and is defined as "the force pushing or pulling the object." Work is defined in CoMPASS as being "done if a force causes an object to move a distance in the same direction as the force" and an algebraic equation is given. Students' ideas of effort force were categorized mainly as a quantity ("how many Newtons it was"), person centered ("the effort force you use"), and pushing, pulling, or lifting something ("effort it takes to pull something"). Students' ideas of work were categorized mainly as person centered ("what you have to do") and labor ("doing something, like sledding"). Overall, effort force was more often considered a quantity than was work. This could be attributed to students measuring effort force in all activities, but only calculating work in one activity. The researchers also identified potential causes of the person-centered view of effort force and work. The view may be attributed to the use of the term "effort force", which may promote the everyday conception of force as exerted by a person. Additionally, the machines were always powered by a person. This study provides possible ideas we may expect the participants in this research to express. In addition, based on the finding that students more often considered force to be a quantity than work, students measure force and calculate work in all activities in this research.

### *2.8.3 Learning by Design™*

The CoMPASS curriculum is broadly based on the ideas of Learning by Design™ (LBD) (Kolodner *et al*., 2003). The goal of LBD is to situate "learning in a purposeful and engaging activity" (pg 496). In order to meet this goal, Kolodner *et al*. have combined many educational strategies and theories, focusing most directly on case-based reasoning and problem-based learning.

Case-based reasoning (CBR) involves reasoning about a present problem based on a previous experience. CBR can involve using an old solution for a new problem, merging several old solutions, using knowledge from a prior situation to interpret a new situation, and guessing the outcome of a new situation based on the outcome of a prior situation. CBR suggests several types of experiences will be especially useful for learning. First, CBR suggests students need to carry out and test their ideas to acquire feedback that will help reveal gaps in the student's knowledge and create new learning goals. Second, CBR suggests students should make predictions, to again reveal gaps in their knowledge, and explain the difference between their prediction and the outcome. Third, CBR suggests students should spend time reflecting on and assessing experiences to determine what can be learned and how what was learned may be used in new situations. Fourth, CBR suggests students will learn more accurately through a process of iterative refinement. Fifth, CBR suggests students should be encouraged to use their own and others' previous experiences when solving new problems. Taken as a whole, these suggestions imply that the act of designing working artifacts or devices is an effective learning experience. These ideas are consistent with constructivism, as students are engaged in building and testing their own knowledge.

Kolodner *et al*. (2003) adapted problem-based learning to solve the problem of classroom management since it provides a structured sequence of classroom practices. Students as a group record known facts, hypotheses and ideas about solving the problem, and issues they would like to learn more about. Students divide up the issues to be pursued, and then use the new information to suggest further solutions to the problem. The cycle continues until an adequate solution is reached and no new learning issues remain. Kolodner *et al*. refined this process into four steps for LBD. First, students construct, test and try to explain how a device works. Second, students experiment with the device to identify the effects of changing specific parameters. Third, students use the results of their experiments to redesign the device. Fourth, students continue this iterative cycle to build the "best" device.

Many of the characteristics of LBD have carried over into the CoMPASS curriculum. In the CoMPASS curriculum for simple machines, students are presented with several "mini-challenges" involving specific simple machines, to prepare them for the overall design challenge of building a complex machine. The challenges are "real-world," with the overall goal of building a machine to help their teacher, who has a broken arm, put away his or her groceries.

During each mini-challenge, the students engage in the same sequence of recording what they already know about the simple machine, generating a list of questions they would like to explore, exploring those topics on the CoMPASS hypertext system, experimenting with the simple machine, and reflecting on the results of their experiment.

## 2.9 Summary

In this chapter I reviewed literature related to both the general aspects of student learning and the specific aspects of comparing student learning with physical and virtual manipulatives. I have described the stances adopted towards constructivism, conceptual understanding, epistemology, and transfer of learning. In addition, I have reviewed the literature related to how students learn with physical and virtual manipulatives, focusing both on the benefits of each and previous studies in physics. Finally, I have described the development of the CoMPASS curriculum, which is used in this study.

This research adopts a constructivist view of learning, using Cobb's theoretical pragmatism to place importance on both the cognitive and social aspects that affect the process of knowledge construction. This research also takes a contemporary and small grain-sized approach to conceptual understanding, epistemology, and transfer of learning. In each of these diverse aspects of student learning, I looked for the productive resources students bring to the learning situation, in the form of conceptual and epistemic resources or concepts and skills used in dynamic transfer. I also investigated whether different resources are activated by the physical and virtual learning environments.

Previous studies that have addressed the issue of how physical and virtual manipulatives support student learning having found mixed results. While some studies have found a difference in learning outcomes in favor of virtual manipulatives, other studies have found no difference. Researchers have called for an expansion of the experimental designs used and the contexts studied. This research aims to fill that niche.

# CHAPTER 3 - Research Methodology

## 3.1 Introduction

The studies described in this dissertation use both qualitative and quantitative research methods, or a mixed methods design. Mixed method designs blend the benefits of qualitative and quantitative methods to understand the phenomenon under study more fully. Quantitative methods provide breadth of understanding, in this study allowing for the analysis of data from many students. On the other hand, qualitative methods provide depth of understanding, in this study allowing for the analysis of the details of how a few students engage with the physical and virtual manipulatives.

In this chapter, I begin by describing the setting in which this research was performed, focusing on the types of participants included and how they were selected. Then, I describe the qualitative research methods used, including the phenomenographic approach used to analyze the qualitative data and steps taken to ensure the validity and reliability of the qualitative results. Next, I describe the quantitative research methods used. Since multiple-choice tests were used to collect the quantitative data, I discuss how the validity and reliability of measuring instruments can be established. Since SPSS was used to analyze the quantitative data, I also describe the steps taken to determine the tests of significance used. Finally, I reformulate the research questions based on the review of literature in Chapter 2 and map the research questions to the types of data collected.

## 3.2 Research Setting

These studies were conducted at Kansas State University, a land-grant institution in Manhattan, Kansas, U.S.A. As of 2010, approximately 18,500 undergraduate and 4,500 graduate students were enrolled in the university. These studies focused particularly on students enrolled in several introductory physics courses. The scope of these courses and their student demographics are described below. I also describe how participants were selected for the studies and how ethical considerations were fulfilled.

### *3.2.1 Introductory Physics Courses*

These studies include participants from several introductory physics courses: *The Physical World*, *Concepts of Physics*, *General Physics*, and *Descriptive Physics*. Below, I describe the scope of these courses and their student demographics.

*The Physical World* (PW) is a three-credit course designed for students with little or no previous experience with physical science. PW covers mainly classical physics with some discussion of modern physics topics. The course is conceptual-based and requires basic mathematics skills, such as arithmetic, but seldom requires algebra or trigonometry. Students may also enroll in a one-credit traditional laboratory component of PW. The lecture and lab are not aligned and not all students enrolled in the lecture enroll in the lab.

*Concepts of Physics* (CoP) is a four-credit course designed for students preparing for careers in elementary education. CoP covers physics concepts that are often presented in elementary school. The course is conceptual-based and requires the same mathematics skills as PW. Emphasis is placed on developing students' qualitative understanding of physics as well as their abilities to teach physics concepts to children. CoP consists of both a lecture and laboratory component. The lab takes place in an Activity Center, which is open at various times throughout the week for students to complete the lab activities at their convenience.

*General Physics* (GP) is a four-credit algebra-based physics course with lecture, laboratory and recitation components. Students are required to have high school level algebra and trigonometry skills. Emphasis is placed on developing students' conceptual understanding and numerical problem solving abilities. The first semester of GP covers mechanics, heat, fluids, oscillations, waves and sound, while the second semester covers electricity and magnetism, light and optics, and atomic and nuclear physics

*Descriptive Physics* (DP) is a five-credit course with lecture, laboratory and recitation components. DP covers topics in mechanics, electricity, heat, light, sound and atomic theory, with an emphasis on how physicists work to understand and describe physical phenomena. Students are required to have the same mathematics skills as GP.

### *3.2.2 Participant Selection*

Participants for this research were selected in several ways, depending on the type of study and nature of the course from which participants were sought. As is described in detail in Chapter 4, two main types of studies were used: interviews and in class implementations.

For the in class implementations, all students enrolled in the laboratory component of the course and present on the day of implementation were included as participants. In class implementations were used in *The Physical World* laboratory and *Concepts of Physics* Activity Center. For one of the in class implementations, volunteers for audio- and/or video recording were solicited. In this case, a researcher visited the lecture to describe the reason for requesting permission to record the students' work. The researcher emphasized that participation in recording was completing voluntary and would not affect the students' grades in the course.

For the interviews, volunteers were solicited from the lectures or laboratories. All students enrolled in the course were given the opportunity to volunteer. Volunteers either received $25 or extra credit in the course, at the lecture professor's preference. During solicitation, the researcher briefly described the study for which students were choosing to volunteer and emphasized that participation was voluntary and would not affect the students' grades in the course (with the exception of extra credit). When extra credit was offered, all students in the course were given a chance to participate. When money was offered, students who wished to volunteer then filled out a form indicating some demographic information and their availability. Participants were then selected based on schedule and to cast a wide net of age, gender, academic major and previous physics background. This is referred to as "convenience sampling" (Gay, Mills and Airasian, 2006).

### *3.2.3 Ethical Considerations*

As human subjects were used in these studies, approval for the research project was received from Kansas State University's Institutional Review Board (IRB). Researchers involved in the project completed the IRB's training modules. When the research involved measures beyond the students' typical classroom work, students signed Informed Consent forms to indicate their willingness to participate in the study. For example, students who participated in interviews signed an Informed Consent form (see Appendix A). For the in-class implementation in which students were audio- or video-recorded, all students signed Informed

Consent forms (see Appendix B) indicating whether they chose to participate in recording. Students were reminded that participating in an interview or allowing audio- or video-recording would not affect their grade in the course, except for any extra credit that may have been offered. Also, students were informed that data collected would remain confidential within the project staff. Pseudonyms are used to protect the participants' identities.

## 3.3 Qualitative Research Methods

In this section, I describe the methods I used to analyze the qualitative data in these studies. Two forms of qualitative data were collected: written answers to worksheet questions and surveys and verbal data from interviews. The phenomenographic approach (Marton, 1986) related to the philosophical approach of phenomenology used to analyze these data is described below. In addition, I describe the learning/teaching interview method that was used in the interview study. Finally, I describe methods used to ensure validity and reliability of the qualitative data analysis.

### *3.3.1 Phenomenology and Phenomenography*

Phenomenology is a philosophy and attitude to human existence often used as a basis for qualitative research (Holloway, 1997). One important concept in phenomenology is phenomenological reduction, which stresses that "things and phenomena are viewed without prior judgment or assumptions; they are seen and described as they appear through *observation* and experience" (Holloway, 1997, pg. 117). Phenomenological reduction requires the researcher to "bracket" their preconceptions.

As phenomenology is not intended as a research method, researchers try not to describe specific techniques used in this approach. However, Colaizzi has described seven steps used in applying phenomenology on a practical level (Holloway, 1997). These steps are:

1. Review collected data to gain a "sense of the whole".
2. Scrutinize the data to "extract significant statements" that are most important for the phenomenon under study.
3. Make sense of the significant statements in the participants' own terms to "formulate meanings." This step uncovers hidden meanings.

4. Organize meanings into “clusters of themes.” This step reveals common patterns. The clusters of themes are taken back to reexamine the data until everything is accounted for.
5. Create an “exhaustive description” of the feelings and ideas related to the themes.
6. Create a description of the phenomenon under study to identify its “fundamental structure.”
7. Perform a “member check” by taking the findings back to the participants to ensure the results accurately and fully reflect the participants’ ideas.

Marton (1986) developed phenomenography as a form of research related to phenomenology. The goal of phenomenography is to “describe phenomena and focus on understanding and variations of experience within the social *context*” (Holloway, 1997, pg. 16). The focus is on how different people understand, experience and interpret phenomena differently. Thus, the results of phenomenographic research are categories of description related to the different ways participants experienced the phenomenon under study.

Phenomenography is useful in education research because, as Marton explains, “a careful account of the different ways people think about phenomena may help uncover conditions that facilitate the transition from one way of thinking to a qualitatively better perception of reality” (1986, pg. 33). Thus, by exploring how various students think about a science concept, a researcher may discover methods to help students transition from scientifically incorrect to scientifically correct conceptions.

A phenomenographic approach is used with the qualitative data in this study. I focused on uncovering the different ways students thought about the science concepts related to pulleys and inclined planes as well as the different associations they made between their prior knowledge and the learning situations. I adapted Colaizzi’s steps for the data analysis. Due to time constraints, I was not able to perform member checks after data analysis.

### *3.3.2 Learning/Teaching Interview*

The learning/teaching interview (Engelhardt *et al.*, 2003) is based on the teaching experiment (Steffe and Thompson, 2000) as opposed to the clinical interview. The clinical interview (Piaget, 1930) aims to uncover students’ understanding of or reasoning about a topic without changing their current knowledge state. On the other hand, the teaching experiment includes “teaching episodes” that give students an opportunity to modify or develop their understanding. Thus, the teaching experiment allows the researcher to develop and test hypotheses about the actual process of student learning. Engelhardt *et al.* (2003) point out several advantages of the teaching experiment. The teaching experiment allows researchers to analyze the effectiveness of different techniques. The teaching experiment also more closely mimics a natural learning environment than does a clinical interview, especially when groups of students are used in a teaching experiment. Recently, we have begun to think of the teaching interview as a learning/teaching interview as a reminder that the emphasis is on the process of student learning.

In this research, learning/teaching interviews were used in pilot testing the curriculum for inclined planes and pulleys. Testing the curriculum first in an interview setting allowed the researcher to more closely monitor the students’ progress and any problems that arose. Learning/teaching interviews were also used at a later stage to gain more information about how students perform experiments with physical and virtual manipulatives. In both cases, the students’ reasoning about simple machines was likely to change as they interacted with scaffolding provided during the interview by the CoMPASS hypertext system, the experiments, and the researcher’s questions.

### *3.3.3 Validity in Qualitative Research*

In qualitative research, validity can be thought of as “the degree to which the qualitative data we collect accurately gauge what we are trying to measure” (Gay *et al.*, 2006, pg. 403). Qualitative researchers tend to use the term trustworthiness or understanding when referring to validity. Guba (1981) and Maxwell (1992) have described how qualitative researchers can establish the trustworthiness of their research.

Guba (1981) describes trustworthiness in terms of credibility, transferability, dependability and confirmability. Credibility refers to taking into account the complexities of the data, such as patterns that are difficult to explain. Transferability refers to including enough detail that others can identify with the setting of the research, since qualitative researchers believe that their studies are context bound. Dependability refers to the stability and confirmability to the neutrality and objectivity of the data.

Maxwell (1981) describes trustworthiness in terms of descriptive, interpretative, theoretical and evaluative validity and generalizability. Descriptive validity refers to factual accuracy, such as verbatim transcripts of participants' quotes. Interpretative validity refers to accurately presenting the data from the participants' perspective. For example, if a participant makes a statement in jest, the researcher must interpret it as a joke (Gay *et al.*, 2006). Theoretical validity refers to the ability of the data analysis to explain the phenomenon being studied. Evaluative validity refers to presenting the data in an unbiased manner. Generaliziblity refers to the extent to which the results apply to the setting that was studied (internal generalizability) and other settings (external generalizability).

In addition, several researchers have described strategies one can use to establish trustworthiness in their data. Among the steps proposed by Guba (1981) are: prolonged participation in the setting, persistent observation, peer debriefing, collecting various forms of "raw" data, member checks, collecting detailed descriptive data, triangulation, and practicing reflexivity. Member checks have already been identified as important to phenomenographic research in Section 3.3.1. Peer debriefing involves discussing your thoughts about the data analysis with a colleague to explore alternatives. Triangulation involves using multiple data sources and data collection strategies to develop a picture that is more strongly supported by the data. Reflexivity is similar to bracketing, described in Section 3.3.1, and involves revealing your own biases to yourself.

Wolcott (1994) has described practical methods for working towards the trustworthiness of qualitative data. As described by Gay *et al.* (2006), these strategies include:

- Listening more than you talk
- Accurately recording observations
- Writing down your reflections
- Including primary data for your readers to interpret
- Reporting discrepant events
- Explicitly stating personal biases
- Seeking feedback from colleagues
- Communicating clearly.

Many of the strategies described by Guba (1981) and Wolcott (1994) were used in this research. For example, peer debriefing and seeking feedback was done at weekly meetings with collaborators, group meetings of and seminars given to the physics education research group at Kansas State University (KSUPER), and presentations at national conferences. Multiple forms of data were collected, including multiple choice and written test questions, worksheet questions, and interviews. After interviews, the researchers often wrote a brief summary of the interview and included their feelings about how the interview had gone. Also, while analyzing data, the researchers attempted to suspend their bias for the scientifically accepted conceptions in order to more accurately understand the students' views.

### *3.3.4 Reliability in Qualitative Research*

Reliability refers to "the degree to which our study data consistently measure whatever they measure" (Gay *et al.* 2006, pg. 407). Qualitative researchers think of reliability in terms of the techniques they use to collect data. The researcher should think about whether the same data would be collected if the same techniques were used again. Gay *et al.* (2006) summarize some of the strategies a researcher can use to establish the reliability of her data (adapted from Schensul, Schensul, and LeCompte, 1999):

- Describing her relationship to the group and the setting
- Documenting observations and interviews through multiple methods, such as notes and recordings
- Documenting and describing the interviewers' training
- Documenting and describing the construction, planning and testing of all instruments
- Documenting sampling techniques.

In this research, I have repeated similar studies in multiple semesters with different students, which contributes to the reliability of the qualitative data. I also took notes and audio- and video-recorded all interviews. The sampling techniques and instrument construction will be described.

It is also important to assess scorer/rater reliability in qualitative data analysis. Interjudge reliability describes how consistently two or more independent scorers code the same data, while intrajudge reliability describes how consistently the same rater codes data over time (Gay *et al.*, 2006). Other members of KSUPER were asked to code data selections to explore interjudge reliability in these studies. In addition, I made multiple passes through the data when coding to ensure that I applied codes in the same way over time.

## 3.4 Quantitative Research Methods

In this study, multiple-choice conceptual tests were used to assess students' knowledge. I describe the construction and basic content of these tests. Then, I describe how validity and reliability of measuring instruments, such as the conceptual tests, can be established. Students' scores on the conceptual tests were compared using statistical tests of significance. Thus, some of the properties that must be considered when selecting a test of significance are also discussed in this section.

### *3.4.1 Multiple-choice Conceptual Tests*

The conceptual tests used in this study are in a multiple-choice format. Osterlind (1998) describes the anatomy and characteristics of a typical multiple-choice test item:

- Directions- should be clear to guide test takers.
- Text and stem- wording should be precise and succinct with correct grammar.
- Graphic- should support the text, but not give any undue clues.
- Distractors- should be plausible.
- Correct response- should be clearly correct.

Osterlind (1998) also describes the criteria for constructing good test items, many of which are important for this research. He states that each test item should be well-matched to the objective of the test; this criteria has to do with validity, and are discussed in more detail below. Also, the test must have a clearly defined objective. The test format should be suitable to the test's goals; uncomplicated goals should be matched with simple item formats. Additionally, test items should be well written.

In this research, I adapted the multiple-choice conceptual tests used by the CoMPASS project staff at the University of Wisconsin, Madison. These collaborators use the CoMPASS curriculum in several middle schools in the Madison, Wisconsin area, and have developed the tests in conjunction with the participating teachers at these schools. The inclined plane and pulley tests covered the same physics concepts, including distance (length of ramp or distance string is pulled), force, work, mechanical advantage, and potential energy. The number of questions and content of the tests varied slightly between the studies, so the specific version of the tests used in each study are described in the following chapters. A sample test used with the pulley curriculum is shown in Appendix C.

### *3.4.2 Validity of Measuring Instruments*

As in qualitative research, validity is very important in quantitative research. In this case, validity is related to the measurement instrument used to collect the quantitative data. Validity of a measurement instrument describes the extent to which the instrument measures what it claims to measure (Gay *et al.*, 2006). Thus, as described by Cronbach in 1971, test validation requires collecting evidence to support the types of inferences that can be drawn from test data. It is not the instrument itself that is validated, but rather the interpretation of the instruments' scores (Osterlind, 1998). Four types of validity—content, criterion-related, construct and consequential—are important to consider and are described below.

Content validity is related to how well a test measures the content area it is intended to represent and requires both item and sampling validity. Item validity is related to whether the specific test questions are relevant to the content area. Sampling validity is related to whether the test fairly represents the entire content area of interest (Gay *et al.*, 2006). For example, a test designed to measure students' knowledge of the physics concepts related to pulleys could have good item validity if all of the questions are related to the physics of pulleys, but poor sampling validity if all of those questions focused on one particular concept, such as force. Content validity requires that test items include only concepts that were actually taught to students, and that the test does not leave out concepts. Content validity can only be determined by expert judgment. In this research, content validity is established by having collaborators, specifically physics graduate students and postdoctoral researchers, review the test items. A summary of their comments is included in Appendix D.

Criterion-related validity is related to how well a participants' score on one test is related to their score on a second test or measure. Criterion-related validity can be concurrent or predictive. Concurrent validity is established by correlating the test score to another test or other measure administered at the same time. Predictive validity describes how well a test can predict an individual's performance in a future situation (Gay *et al.*, 2006). Predictive validity is important for tests used to classify or select participants, which is not the intent of this research. Since students answered worksheet questions immediately before taking the mid- and post-tests in these studies, their answers to the worksheet questions can help to establish concurrent validity.

Construct validity describes how well a test actually measures the intended construct. Gay *et al.* (2006) state “it is the most important form of validity because it asks the fundamental validity question: What is this test really measuring?” (pg. 137). A measuring instrument has construct validity if it measures the intended construct and not some other variable. No single validation study can confirm construct validity, but combinations of content and criterion-related validity can be used to establish construct validity.

Consequential validity describes the risks to participants, such as students and teachers, associated with the test. For example, it may be unfair to judge non-English speakers with the same test as English speakers (Gay *et al.*, 2006). In these studies, there is a possible threat to consequential validity as the tests were in some cases used to determine a students’ lab score or extra credit score. To alleviate this risk, only a small portion (about 20%) of students’ scores was determined by the number of test questions they answered correctly; most of the student’s grade was based on completion of the activities, worksheets and tests.

Gay *et al.* (2006) also describe some possible threats to the validity of measuring instruments. These include:

- Lack of clear test directions
- Confusing or ambiguous questions
- Unfamiliar or difficult vocabulary
- Complex sentences
- Inconsistent or subjective scoring
- Including untaught concepts
- Not following the given test administration procedures
- Cheating

We kept these possible threats in mind when constructing and administering the tests. Middle school science teachers reviewed the tests for difficult vocabulary and sentence structures. A member of the research team was present whenever the tests were administered to ensure proper procedures were followed and to minimize cheating.

### *3.4.3 Reliability of Measuring Instruments*

Gay *et al.* (2006) describe how reliability applies to measurement instruments. Reliability describes how consistently a test measures what it is intended to measure. Reliability comes in many forms and is generally expressed as a reliability coefficient using correlation. Test-retest reliability describes the correlation of scores on the same test by the same participants at two different times. This is important for tests used to make predictions. Equivalent-forms reliability describes the correlation of scores from the same participants on similar forms of a test. This is the most common form of reliability used for tests and research. A researcher could combine these two forms of reliability by giving two forms of a test at two different times to the same participants; a correlation between the two tests would then establish the coefficient of stability and equivalence.

Equivalent-forms reliability of the pulley test was explored in an interview study conducted by summer undergraduate researcher Amy Rouinfar. She found students tended to give consistent responses to the written pulley test questions and similar verbal questions that had a different context (Rouinfar, Chini, Carmichael, Puntambekar and Rebello, 2010).

Internal consistency reliability describes the consistency of the individual items on a particular test, or how consistently the test items measure the same construct. Internal consistency reliability can be calculated three ways, and each requires just one administration of a single test. Split-half reliability is calculated by dividing the test in half and correlating the scores on the two halves. The halves should be selected to be comparable, which is often achieved by correlating even and odd items. The Spearman-Brown prophecy formula is used to correct the correlation formula to represent the whole test. The Kuder-Richardson 20 (KR-20) and Cronbach’s alpha compute the average of the split-half reliability for all possible combinations. The KR-20 can only be used with dichotomous scoring so the Cronbach alpha is used when an item can have more than two responses. The KR- 21 uses a simpler formula than the KR-20 and yields a more conservative estimate of reliability.

Cronbach’s alpha was used to assess the internal consistency reliability of the tests. The results are displayed in Table 3.1 below.

**Table 3.1 Cronbach's Alpha for Pulley and Inclined Plane Tests**

| Topic | Study | Cronbach’s Alpha |
|---|---|---|
| Inclined Plane | Physical World Spring 2009 | 0.484 |
| Inclined Plane | Physical World Fall 2009 | 0.933 |
| Pulley | Physical World Spring 2009 | 0.772 |
| Pulley | Physical World Fall 2009 | 0.667 |
| Pulley | Concepts of Physics Fall 2009 | 0.728 |

### *3.4.4 Statistical Tests of Significance*

SPSS and SAS were used for analysis of the quantitative data in these studies. Statistical tests of significance allow researchers to determine whether two or more group means are different enough to represent a true difference (Gay *et al.*, 2006). A number of factors, such as the type of data, number of groups, and method of participant selection, determine which statistical test is appropriate to use for a given comparison. Below, I describe the assumptions of the two main types of statistical tests: parametric and nonparametric. Then, I describe the various statistical tests used in this research and the conditions under which each should be used.

Parametric tests are considered to be "more powerful" than nonparametric tests because they are more likely to conclude correctly that a true difference exists between group means. A statistical test has two possible conclusions: the difference in group means is significant and represents a true difference or the difference in group means is not significant and does not represent a true difference but is the result of chance. Thus, there is the possibility for two types of errors to occur. If the difference is actually the result of chance, but the statistical test concludes it is a true difference, a Type I error is committed. If the difference represents a true difference, but the statistical test concludes it is the result of chance, a Type II error is committed. In this language, parametric tests are less likely than nonparametric tests to commit a Type II error. The probability of committing a Type I error is determined when the researcher selects a probability level, or $\alpha$-level (Gay *et al.*, 2006). In this research, the $\alpha$-level was either $\alpha=0.05$ or $\alpha=0.025$, depending on how many comparisons were made between the data.

While parametric tests are more powerful, they also require that the data meet four assumptions, which are described by Field (2005). First, the data must be normally distributed. The normality of data can be checked by "eyeballing" a histogram or by using the Kolmogorov-Smirnov or Shapiro-Wilk tests in SPSS. A combination of both methods is recommended since it is easy to get a significant result from a small deviation from normality with a large population size. The second assumption of parametric tests is that the variances between the two groups are the same; this is called homogeneity of variance. Homogeneity of variance can be determined by using Levene's test in SPSS or by calculating the ratio of the highest variance compared to the lowest variance. A ratio of less than 2 is assumed to satisfy this assumption. The third assumption is that the data is measured at the interval or ratio level, which means it is based on predetermined equal intervals (i.e. the difference between scoring an 85% and a 90% on the test is the same as the difference between scoring a 65% and a 70%). Finally, the fourth assumption is that the selection of participants is independent.

Nonparametric tests make fewer assumptions than parametric tests, but are less powerful. It is appropriate to use nonparametric tests when a parametric assumption is greatly violated or the data is not measured at interval or ratio level (Gay, Miller and Airasian, 2006).

Students' performance on the conceptual tests was analyzed with either an ANCOVA or a mixed-ANOVA. The ANCOVA was used in Inclined Plane Study #1 because students took only a pre-test and post-test. I conducted this analysis using SPSS software. Pre-test score was used as a covariate and treatment (manipulative used and experiments performed) were used as between-subjects factors. Contrasts were performed to determine which groups significantly differed from other groups. A Bonferroni correction was applied to reduce the chance of Type-1 errors.

For the remainder of the class studies, students took a pre-test, mid-test and post-test. Since the treatments (physical-virtual or virtual-physical sequence) were applied to entire laboratory sections (as described in Chapter 4), laboratory section was the experimental unit and individual students needed to be layered within laboratory section for the most careful and conservative statistical results. This analysis could not be performed in the SPSS software, and was instead conducted with SAS software in consultation with Dr. Leigh Murray and Zhining Ou of the Kansas State University Statistics Department. For the mixed-ANOVA, test (at the levels pre-, mid- and post-) was used as a within-subjects factor, and laboratory section and treatment were used as between-subjects chapters. Bonferroni-adjusted contrasts were used to explore between which levels of test the effects (test and treatment) were significant.

I conducted chi-square test of independence analysis on the worksheet and survey data using SPSS. The chi-square test is appropriate for this data because the data is categorical. Contingency tables were formed with treatment and categories of response for questions of interest. In the contingency table, the researcher records the number of observations of a specific response within a specific treatment. Once the table is complete, the number of observations one would expect to find if the two treatments were not different is calculated; this is called the expected frequency. If any cell within the contingency table has an expected frequency less than

5, it is safer to use Fisher's exact test because the chi-square distribution breaks down for low frequencies (Agresti, 2002). When the overall result for the contingency table is significant (which indicates that the two treatments are different), adjusted residuals can be examined to identify the cells on which the treatments exhibit independence. Adjusted residuals larger than 1.96 indicate a significant cell (Haberman, 1973).

## 3.5 Research Questions Revisited

As discussed in Chapter 1, the goal of this research is to compare how students' learning about the physics concepts related to pulleys and inclined planes is supported by performing experiments with physical equipment, computer simulations, and a combination of both. I assessed students' learning in three ways, focusing on:

1. *What* students learn
2. *How* students learn, and
3. What students *think about* their learning

### *3.5.1 Reformulation of Research Questions*

Based on the literature review in Chapter 2, these questions can be reformulated to connect more explicitly with the theoretical background of this research. In these studies, I assessed:

1) What do students learn from the physical activities, and what do they learn from the virtual activities?
    a) Do students' written responses to data analysis questions differ between the physical and virtual experiments or the physical-virtual and virtual-physical sequences?
    b) Do the physical and virtual manipulatives or physical-virtual and virtual-physical sequences provide different support for students' conceptual understanding?
    c) When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity?
2) Do the environments created by the physical and virtual manipulatives offer different support for dynamic transfer? What features of each environment create the support? Can the support offered by one environment be recreated in the other?
3) Do students view the information from physical and virtual manipulatives differently? Is there evidence that different epistemic resources are activated by the two contexts?

### *3.5.2 Mapping of Research Questions to Research Methods*

Table 3.2 below shows the types of data that were used to address each of the research questions. In the following chapters I describe the studies in which these data were collected in detail.

**Table 3.2 Mapping of Research Questions to Data Collected**

| **Research Question** | **Types of Data** |
|---|---|
| 1. *What* students learn | • Multiple choice questions on pre-, mid- and post-tests<br>• Open-ended questions on worksheets |
| 2. *How* students learn | • Interviews |
| 3. What students *think* about their learning | • Open-ended questions where students compare physical and virtual experiments<br>• Survey questions where students select which type of data (from a physical or virtual experiment) would be more useful for a certain situation |

## 3.6 Summary

In this chapter, I described the qualitative and quantitative research methods used in these studies. Marton's (1986) phenomenographic approach was used for the qualitative analysis, while SPSS and SAS were used to run statistical tests of significance for the quantitative data. This chapter described many methods that have been identified as useful in establishing the validity and reliability of both qualitative and quantitative results. In addition, this chapter identified the statistical tests that were used in these studies. Finally, the research questions were reframed using the theoretical background from Chapter 2 and mapped to the data collected in the studies.

# CHAPTER 4 - Description of Studies

## 4.1 Introduction

In this chapter, I describe the studies that are presented in the following chapters. I describe the participants involved, the curriculum used, and the format of each study.

## 4.2 Pulley Studies

Four studies were conducted to explore how students' learning about the physics concepts related to pulleys was influenced by the use of physical and virtual manipulatives. The studies involved different groups of student participants, different formats, and different variations of the pulley curriculum. Each is described in detail below.

### *4.2.1 Pulley Study #1: Physical World Spring 2009 (PWS09)*

The CoMPASS pulley curriculum was used in the Physical World laboratory in the Spring 2009 semester. In this section, I describe the study design, curriculum and tests used in the Physical World Spring 2009 (PWS09) implementation.

#### *4.2.1.1 Study Design*

In Spring 2009, the Physical World laboratory had five sections, which met for two hours each. Each section was led by one of three teaching assistants, and during the implementation at least one researcher was present to help answer students' questions. Three sections used physical manipulatives followed by virtual manipulatives to complete the activities (PV sequence), while two sections used virtual manipulatives followed by physical manipulatives (VP sequence). The details of each section's conditions are summarized in the Table 4.1 below.

**Table 4.1 Physical World Spring 2009 Section Descriptions for Pulley Study**

| Section | N | Manipulatives |
|---|---|---|
| A | 33 | Physical-Virtual |
| B | 31 | Virtual-Physical |
| C | 22 | Physical-Virtual |
| D | 28 | Physical-Virtual |
| E | 30 | Virtual-Physical |

Students took a pre-test before beginning the instruction, a mid-test after completing one set of activities, and a post-test after completing the second set. They recorded data from their experiment and responded to worksheet questions during each set of activities. The worksheets and tests are described in the following sections.

This design allows for several comparisons. The effectiveness of the physical and virtual manipulatives alone can be assessed by comparing mid-test scores and students' responses to their first set of worksheet questions. The effectiveness of the physical-virtual and virtual-physical sequences can be assessed by comparing post-test scores. Whether there is added value from completing both sets of activities can be assessed by comparing students' mid-test scores to their post-test scores.

#### *4.2.1.2 Curriculum*

The worksheets from the PWS09 implementation are included in Appendix E. The physical-virtual (PV) and virtual-physical (VP) sequences began with the same introductory questions. All students began by reading about the "Pulley Challenge", which gave them the task of discovering the best way to use pulleys to lift a pool table into a van. Next, students recorded their individual predictions about the factors that would affect the force and work needed to lift an object using a pulley setup. Then, with their group, students recorded their predictions about the best way to set up pulleys to reduce the force needed to lift an object. The groups then created a list of questions to guide their research in the CoMPASS hypertext system about the science concepts and "non-science" issues related to pulleys. Next, students used the CoMPASS hypertext system to explore the science concepts related to pulleys.

After using the CoMPASS website, students began their first activity. Students in the PV sequence used physical equipment, as shown in Figure 4.1, while students in the VP sequence used a pulley simulation, as shown in Figure 4.2. All students tested the single fixed, single movable, single compound, and double compound pulley systems. Diagrams of these pulley setups are displayed in Figure 4.3 below. Students using the physical equipment had to construct and string their pulley systems by hand, while students using the virtual equipment clicked on the pulley setup in the simulation. Students in both conditions recorded the same data, including direction of force, force, distance pulled to move object, distance object moved, work, potential energy and mechanical advantage. Students using physical equipment had to make measurements with a spring scale and meter stick and calculate work, potential energy, and mechanical advantage. The simulation displayed the distances, force and work, but students using the virtual manipulative still had to calculate potential energy and mechanical advantage.

Figure 4.1 Pulley physical manipulative.

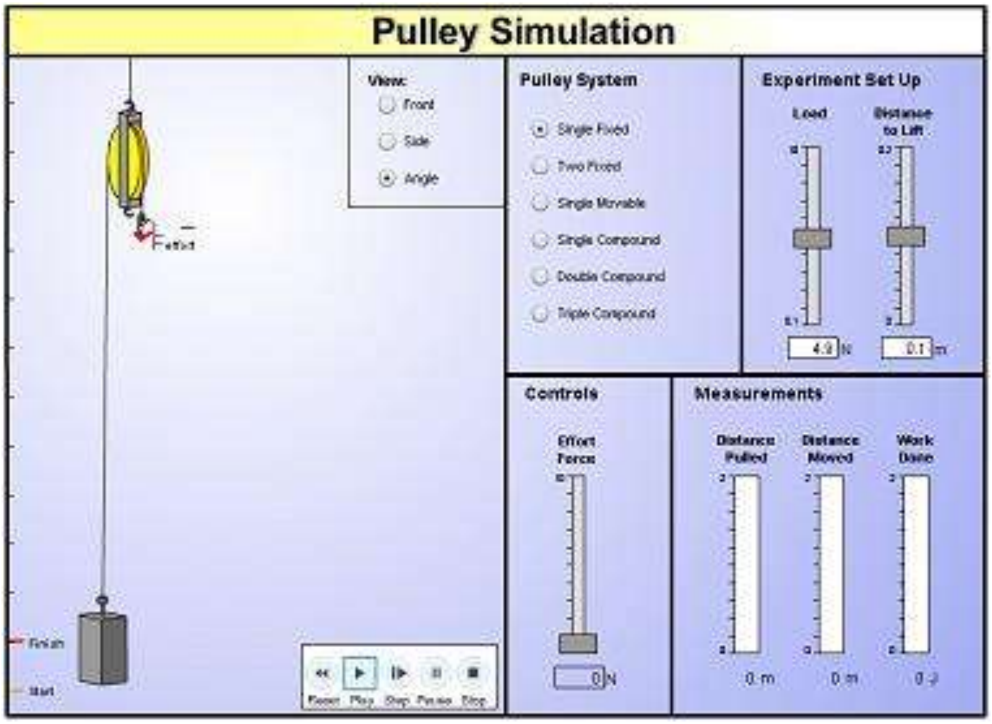


Figure 4.2 Pulley virtual manipulative.

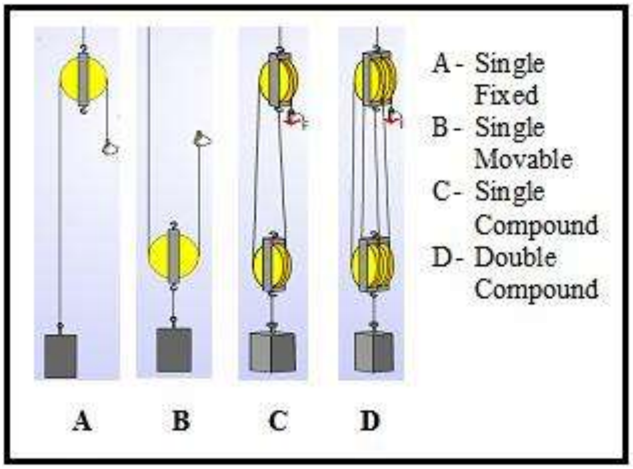


**Figure 4.3 Pulley setups.**

After completing the experiment, students in both conditions answered analysis questions on their worksheets. These questions are shown in the worksheet in Appendix E. Students in both sections answered the same analysis questions, which focused on force, distance, work, potential energy, and mechanical advantage. The questions are detailed in the following section.

After completing the mid-test, students repeated the experiments with the other manipulative. Students who had first used the physical equipment now used the simulation, and students who had first used the simulation now used the physical equipment. After completing the experiments, students answered the analysis questions again. Two additional questions asked the students to make comparisons between the relationships in their data from the physical experiment with the relationships in their data from the virtual experiment. Specifically, students were asked to explain any differences in the relationships between work and potential energy and mechanical advantage and number of supporting strands between the data from the physical and virtual experiments.

Finally, students responded to the initial challenge by describing the best way to use pulleys to lift a pool table into a van and took the post-test. Students also answered feedback questions about which experiment was more helpful, which experiment was more enjoyable, any part of the activities that seemed not related to the challenge, and which science concepts seemed related to the challenge.

#### *4.2.1.3 Assessment of Student Learning*

Students' worksheets included analysis questions that were used to examine what students learned by performing the physical and virtual experiments. (See the PWS09 worksheets in Appendix E for the analysis questions as they were presented to students.) The questions are reproduced in Table 4.2 below. WQ1 through WQ7 were asked after each experiment in both treatment sequences. WQ8 and WQ9 were asked after the second experiment in both treatment sequences because they required comparison between the students' two data sets. In the PV sequence, the students answered WQ8 and WQ9 after completing the virtual experiment, while in the VP sequence, the students answered WQ8 and WQ9 after completing the physical experiment.

**Table 4.2 PWS09 Pulley Worksheet Questions**

| Question # | Worksheet Analysis Questions |
|---|---|
| WQ1 | Based on your data, which pulley setup required the **smallest effort (force)** to lift the load? |
| WQ2 | Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required? |
| WQ3 | Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*? |
| WQ4 | Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object? |
| WQ5 | Based on your data, how does **work** compare to **potential energy** for a given pulley system? |
| WQ6 | Which pulley setup gave you the *greatest* **mechanical advantage**? |
| WQ7 | Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**? |
| WQ8* | How does the relationship between **work** and **potential energy** in the *experiment* compare with the *simulation*? |
| WQ9* | How does the relationship between **mechanical advantage** and the **number of supporting strands** in the *experiment* compare with the *simulation*? |

*Question asked only once, after students completed both experiments.

The test used in this study is included in Appendix C. The same test was used for the pre-test, mid-test and post-test, except the "explain your reasoning" questions were removed for the mid-test. The test consisted of eleven multiple-choice questions, two calculations, and one open-ended question. Two multiple-choice questions asked students to explain their reasoning.

Table 4.3 below summarizes the format of each question and the concept and pulley setups tested.

**Table 4.3. PWS09 Pulley Test Breakdown**

| Q # | Format | Main Physics Concept | Pulley Setup(s) |
|---|---|---|---|
| 1 | Multiple-choice | Force | Single fixed; Single movable |
| 2a | Multiple-choice | Distance | Single fixed; Single movable |
| 2b | Multiple-choice | Force | Single fixed; Single movable |
| 3 | Multiple-choice | Force | Single fixed; Two single fixed |
| 4 | Open-ended | Force | Single movable |
| 6a | Multiple-choice | Force | Single fixed; Single movable |
| 6b | Multiple-choice | Work | Single fixed; Single movable |
| 7 | Calculation | Work | Single movable |
| 8 | Multiple-choice | Work | Single fixed |
| 9 | Multiple-choice | Work | Single fixed; Single compound; Double compound |
| 11 | Multiple-choice | Mechanical advantage | Single fixed; Single movable |
| 12 | Multiple-choice | Mechanical advantage | Single fixed; Two single fixed |
| 13 | Multiple-choice | Work/Potential energy | Single movable |
| 14 | Multiple-choice/ Calculation | Potential energy | Single movable |

#### *4.2.1.4 Research Questions Addressed*

This study addresses Research Question 1 (RQ1), which focuses on students' conceptual learning. Specifically, RQ1 asks:

- What do students learn from the physical activities, and what do they learn from the virtual activities?
- When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity?
- When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other?

The first part of RQ1, what students learn from the physical and virtual activities, was addressed by analysis of students' first set of worksheet questions and their performance on the mid-test. The second part of RQ1, whether students continue to learn in their second activity, was addressed by comparing students' performance on the mid-test with their performance on the post-test. The third part of RQ1, is one treatment sequence more beneficial than the other, was addressed by analysis of the students' second set of worksheet questions and their performance on the post-test. Table 4.4 below summarizes how the data was used to address RQ1.

**Table 4.4 Mapping of PWS09 Pulley Data to Research Questions**

| **Research Question** | **Relevant Data** |
|---|---|
| What do students learn from the physical activities, and what do they learn from the virtual activities? | Mid-test scores; First set of worksheet questions |
| When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity? | Mid-test and post-test scores within the same sequence |
| When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other? | Post-test scores; Second set of worksheet questions |

### *4.2.2 Pulley Study #2: Physical World Fall 2009 (PWF09)*

A modified version of the CoMPASS curriculum was used in the Physical World laboratory in the Fall 2009 semester. In this section, I describe the study design, curriculum and tests used in the Physical World Fall 2009 (PWF09) implementation.

#### *4.2.2.1 Study Design*

In Fall 2009, the Physical World laboratory had four sections, which met for two hours each. Each section was led by one of two teaching assistants, and during the implementation at least one researcher was present to help answer students' questions. Two sections used physical manipulatives followed by virtual manipulatives to complete the activities, and two sections used virtual manipulatives followed by physical manipulatives. The details of each section's conditions are described in Table 4.5 below.

**Table 4.5 Physical World Fall 2009 Section Descriptions for Pulley Study**

| **Section** | **N** | **Manipulatives** |
|---|---|---|
| A | 28 | Virtual-Physical |
| B | 34 | Physical-Virtual |
| C | 30 | Virtual-Physical |
| D | 33 | Physical-Virtual |

Similar to the format of the PWS09 Pulley Study, students took a pre-test before instruction, a mid-test after completing one set of activities, and a post-test after completing the second set of activities. Thus, this study allows for similar comparisons as the PWS09 study. The effectiveness of the physical and virtual manipulatives alone can be assessed by comparing students' mid-test scores and their first set of worksheet questions. The effectiveness of the two sequences can be assessed by comparing students' post-test scores and their second set of worksheet questions. Whether there is added value from completing both sets of activities can be assessed by comparing students' mid-test scores to their post-test scores.

#### *4.2.2.2 Curriculum*

The worksheets from the PWF09 implementation are included in Appendix F. The curriculum was very similar to that used in the PWS09 implementation, so I highlight the differences between the two curricula in this section. Students began by reading the "Pulley Challenge", which gave them the task of discovering the best way to use pulleys to lift a pool table into a van. However, in the PWF09 implementation students were not asked to make predictions about pulley systems. The prediction questions were removed to allow the students more time to work on the activities. Next, similar to the PWS09 study, the groups created a list of questions to guide their research in the CoMPASS hypertext system and used that system to explore the science concepts related to pulleys.

After using the CoMPASS website, students began their first activity. Students used the same manipulatives (shown in Figure 4.1 and Figure 4.2 above) to collect the same data as in the PWS09 study. See section 4.2.1.2 above for a thorough description of the activities. Two changes were made to the data table students used to record their findings. First, the column "Direction of Force Changed?" was reworded to read "Does the object move in the *same* direction as the applied force?" This change was made because students often had questions about the meaning of the first phrase. Second, the column "Rank Your Best Trial" was removed. Again, students often had questions about what to do in this column, and it did not seem to aid their understanding.

After completing the experiment, the students answered the same analysis questions as in the PWS09 study, reproduced in Table 4.2 above. Students then took the mid-test. After the mid-test, students completed the second set of activities and answered the analysis questions.

Students who had previously used the physical equipment used the simulation, and students who had previously used the simulation used the physical equipment.

Next, students responded to the initial challenge by describing the best way to get the pool table into the van using pulleys and took the post-test. Students also responded to several feedback questions about which set of activities was more helpful, more enjoyable and more trustworthy.

#### *4.2.2.3 Assessment of Student Learning*

Students' worksheets included analysis questions (WQ) that were used to examine what students learned by performing the physical and virtual experiments. See the PWF09 worksheets in Appendix F for the analysis questions as they were presented to students. The questions were the same as those asked in the PWS09 study and are reproduced in Table 4.2 above. Again, WQ1 through WQ7 were asked after each experiment in both treatment sequences. WQ8 and WQ9 were asked after the second experiment since they required comparison between the data sets from both experiments.

The test used in this study is included in Appendix G. The same test was used for the pre-test, mid-test and post-test. Students completed the test on Scantron forms and answered the calculation question on a separate sheet of paper. Scantron forms were used to reduce the amount of paper necessary for printing three copies of the test per student. Significant changes were made from the test used in the PWS09 study. The phrase "if we ignore friction" was added to make the questions more physically correct, although there is no evidence that students were previously explicitly considering friction when making their answer choices. A summary of the questions' format and the concepts and pulley systems tested is shown in Table 4.6 below. An asterisk is used to indicate new questions added since the PWS09 implementation. These questions were added to make the pulley test questions better align with the inclined plane test questions.

**Table 4.6 PWF09 Pulley Test Breakdown**

| Q# | Format | Main Physics Concept | Pulley Setup(s) |
|---|---|---|---|
| 1 | Multiple-choice | Force | Single fixed; Single movable |
| 2* | Multiple-choice | Force | Single compound; No pulley |
| 3 | Multiple-choice | Distance | Single fixed; Single movable |
| 4 | Multiple-choice | Force | Single fixed; Single movable |
| 5* | Multiple-choice | Force | Single fixed: well-oiled vs. sticky |
| 6* | Multiple-choice | Force | Single fixed; Single compound |
| 7* | Multiple-choice | Force | Single fixed; Two single fixed; Single movable; Double compound |
| 8 | Multiple-choice | Force | Single fixed; Single movable |
| 9 | Multiple-choice | Work | Single fixed; Single movable |
| 10* | Multiple-choice | Work | Single compound; No pulley |
| 11* | Multiple-choice | Work | Single fixed: well-oiled vs. sticky |
| 12 | Multiple-choice | Work | Single fixed |
| 13 | Multiple-choice | Work | Single fixed; Single compound; Double compound |
| 14* | Multiple-choice | Mechanical advantage | One single fixed; Two singled fixed, Single movable; Double compound |
| 15 | Multiple-choice | Mechanical advantage | One single fixed; Two single fixed |
| 16 | Multiple-choice | Mechanical advantage | Single fixed; Single movable |
| 17* | Multiple-choice | Potential energy | Single compound |
| 18* | Multiple-choice | Potential energy | Single fixed; Single compound |
| 19* | Multiple-choice | Work/potential energy | Double compound (well-oiled) |
| 20* | Multiple-choice | Work/potential energy | Double compound (needs to be oiled) |
| 21 | Calculation | Work | Single movable |

Several questions from the PWS09 test were removed. As numbered in Table 4.3 above, the questions removed were: 3, 4, 13 and 14. Question 3, which was about force, was removed because several additional questions about force had been added. Question 4 was removed because it was similar to a question asked in the worksheet. Questions 13 and 14, which were about potential energy, were removed because additional questions about potential energy had been added. As mentioned above, changes were made to the pulley test to improve the alignment between the pulley and inclined plane test questions. These better-aligned tests allow for better comparisons of student learning about the two simple machines.

#### *4.2.2.4 Research Questions Addressed*

As with the PWS09 study, this study addresses Research Question 1 (RQ1). The use of the pre-test/mid-test/post-test design allows for comparison of the physical and virtual manipulatives alone, comparison of the physical-virtual and virtual-physical sequences, and assessment of the added benefit of performing the second activity. See Table 4.4 above for a summary of how the data was used to address these questions. Because the conceptual test was changed to be in better alignment with the inclined plane conceptual test, this study allows for better comparison of students' learning about the two simple machines. Thus, this study helps to test the generalizability of the results of the pulley studies.

### *4.2.3 Pulley Study #3: Concepts of Physics Fall 2009 (CoPF09)*

The CoMPASS pulley curriculum was used in the Concepts of Physics Activity Center in the Fall 2009 semester. In this section, I describe the study design, curriculum and test used in the Concepts of Physics Fall 2009 (CoPF09) implementation.

#### *4.2.3.1 Study Design*

The Concepts of Physics laboratory has a non-traditional structure. Rather than having a set class time, the laboratory takes place in an Activity Center. The Activity Center is open at scheduled times throughout the week and students can work on the current week's laboratory at their own pace during those scheduled times.

The CoPF09 study followed the same basic design as the PWS09 and PWF09 studies, but the timing was different. Students again took a pre-test, mid-test and post-test. However, the pre-test was administered in the lecture meeting before the pulley activity began in the Activity Center. Students then went to the Activity Center and completed the physical and virtual experiments in the order of their choosing. Fifty-nine students performed the activities in the physical-virtual (PV) sequence, and 40 students performed the activities in the virtual-physical (VP) sequence. Students took the mid-test in the Activity Center between the two experiments. However, the post-test was administered in the lecture meeting after the pulley activity ended in the Activity Center. Thus, the time between performing the activities and taking the post-test was longer in the CoPF09 study than the previous studies. In addition, the time between the activities and the post-test varied by student since students completed the activities at different times.

Two additional types of information were collected in this study to assess students' views about performing experiments with physical and virtual manipulatives. First, students responded to a set of "Wrap Up Questions" in the Activity Center after completing their second set of activities. These questions assessed students' understanding of the similarities and differences between the physical and virtual experiments. The survey is included in Appendix H, and the questions are displayed in Table 4.7 below. Students also responded to a survey about when they would use data from physical and virtual manipulatives. This survey was administered after students completed the post-test in their lecture. These questions were designed to investigate whether certain contexts, concepts or pulley setups would affect the type of equipment students would choose to use to perform an experiment. The survey is included in Appendix I, and the questions are summarized in Table 4.8 below.

**Table 4.7 CoPF09 Wrap Up Questions**

| **Q#** | **Question** |
|---|---|
| Q1 | In what ways was the computer simulation pulley experiment *similar* to the physical pulley experiment? |
| Q2 | In what ways was the computer simulation pulley experiment *different* from the physical pulley experiment? |
| Q3 | What may have caused differences between the data you got from the physical pulley experiment and the data you got from the computer simulation experiment? |
| Q4 | If there were differences between the data from your physical pulley experiment and your computer simulation experiment, which would you trust more? |

**Table 4.8 CoPF09 Manipulative Preference Survey**

| **Q#** | **Context** | **Concept** | **Pulley Setups** |
|---|---|---|---|
| 1a | Exam | Force | Single fixed and single movable |
| 1b | Exam | Work | Single fixed and single movable |
| 1c | Exam | Force | Single movable and double compound |
| 1d | Exam | Work | Single movable and double compound |
| 2a | Rental Store | Not specified | Single fixed and single movable |
| 2b | Rental Store | Not specified | Single movable and double compound |
| 3a | Missed Lab | Force | Not specified |
| 3b | Missed Lab | Work | Not specified |

#### *4.2.3.2 Curriculum*

The worksheets used in the COPF09 implementation are included in Appendix J. The students began with Packet A, which included the pre-experiment activities. Students began by reading the “Pulley Challenge” and making predictions about the factors that would affect the force and work needed to lift an object using the pulley setup, as in the PWS09 study. Next, students worked with their group members to discuss their predictions and develop a list of questions about pulleys to guide their research in the CoMPASS hypertext system. Students then used the hypertext system to explore some of the science concepts related to pulleys.

After using the hypertext system, students chose whether to perform the physical or virtual experiment first. Students used the same manipulatives as in the PWS09 and PWF09 studies, pictured in Figures 4.1 and 4.2 above, to explore the pulley systems pictured in Figure 4.3. Students used the same data table as in the PWS09 study. See section 4.2.1.2 for a more thorough description of the activities. As in the previous studies, students completed the mid-test in the Activity Center in between the two experiments. In the COPF09 study, students did not respond to the initial challenge but instead completed the Wrap Up Questions described above.

#### *4.2.3.3 Assessment of Student Learning*

Students' worksheets included analysis questions that were used to examine what students learned by performing the physical and virtual experiments. Students answered many of the same analysis questions as in the PWS09 and PWF09 studies; these questions are reproduced in Table 4.3 above. Questions WQ1 through WQ7 were again answered after each experiment. However, WQ8 and WQ9, which asked students to compare the physical and virtual data, were removed since students chose the order in which they completed the activities.

The test used in this study is included in Appendix K. The same test was used for the pre-test, mid-test and post-test. The same questions were asked as in the PWF09 study. However, the order and numbering was different and "explain your reasoning" questions were included. These changes are indicated in Table 4.9 below. These differences arose because Scantron forms were used in the PWF09 study. The decision was made to print personal copies of the test for each student so that the "explain your reasoning" information could be collected.

**Table 4.9 CoPF09 Pulley Test Breakdown**

| Q# | Format | Main Physics Concept | Pulley Setup(s) |
|---|---|---|---|
| 1 (1) | Multiple-choice | Force | Single fixed; Single movable |
| 2 (2) | Multiple-choice | Force | Single compound; No pulley |
| 3a* (3) | Multiple-choice | Distance | Single fixed; Single movable |
| 3c* (4) | Multiple-choice | Force | Single fixed; Single movable |
| 5 (5) | Multiple-choice | Force | Single fixed: well-oiled vs. sticky |
| 6 (6) | Multiple-choice | Force | Single fixed; Single compound |
| 7 (7) | Multiple-choice | Force | Single fixed; Two single fixed; Single movable; Double compound |
| 8a* (8) | Multiple-choice | Force | Single fixed; Single movable |
| 8b* (9) | Multiple-choice | Work | Single fixed; Single movable |
| 9 (21) | Calculation | Work | Single movable |
| 10* (10) | Multiple-choice | Work | Single compound; No pulley |
| 11 (11) | Multiple-choice | Work | Single fixed: well-oiled vs. sticky |
| 12* (12) | Multiple-choice | Work | Single fixed |
| 13 (13) | Multiple-choice | Work | Single fixed; Single compound; Double compound |
| 14* (14) | Multiple-choice | Mechanical advantage | One single fixed; Two singled fixed, Single movable; Double compound |
| 15* (15) | Multiple-choice | Mechanical advantage | One single fixed; Two single fixed |
| 16 (16) | Multiple-choice | Mechanical advantage | Single fixed; Single movable |
| 17 (17) | Multiple-choice | Potential energy | Single compound |
| 18 (18) | Multiple-choice | Potential energy | Single fixed; Single compound |
| 19 (19) | Multiple-choice | Work/potential energy | Double compound (well-oiled) |
| 20 (20) | Multiple-choice | Work/potential energy | Double compound (needs to be oiled) |

#### *4.2.3.4 Research Questions Addressed*

As with the PWS09 and PWF09 studies, this study addresses Research Question 1 (RQ1). The use of the pre-test/mid-test/post-test design allows for comparison of the physical and virtual manipulatives alone, comparison of the physical-virtual and virtual-physical sequences, and assessment of the added benefit of performing the second activity.

This study also addresses Research Question 3 (RQ3), which focuses on students' views of the physical and virtual experiments. Specifically, RQ3 asks, "Do students view the information from physical and virtual manipulatives differently?" RQ3 is addressed by the Wrap Up Questions, shown in Table 4.7 above, which students answered after completing the experiments, and the survey, described in Table 4.8 above, which students completed after the post-test. The Wrap Up Questions probe students' understanding of the differences between the physical and virtual experiments. The survey questions probe students' views of the usefulness of data from the two types of experiments. The mapping of the data to the research questions is summarized in Table 4.10 below.

**Table 4.10 Mapping of CoPF09 Data to Research Questions**

| **Research Question** | **Relevant Data** |
|---|---|
| **RQ1a:** What do students learn from the physical activities, and what do they learn from the virtual activities? | Mid-test scores; First set of worksheet questions |
| **RQ1b:** When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity? | Mid-test and post-test scores within the same sequence |
| **RQ1c:** When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other? | Post-test scores; Second set of worksheet questions |
| **RQ3:** Do students view the information from physical and virtual manipulatives differently | Wrap Up Questions *(differences between physical & virtual)*<br>Survey *(when to use physical or virtual)* |

### *4.2.4 Pulley Study #4: PWS10*

The pulley study was repeated in the Physical World laboratory in Spring 2010. This implementation was mainly run by other members of the Kansas State University project staff so most of the data was not included in this dissertation. However, due to some unexpected results of the survey about the usefulness of the physical and virtual experiments in the COPF09 study, the survey was edited and the new version was used in the PWS10 study.

#### *4.2.4.1 Study Design*

In the PWS10 study, the pulley experiments were broken across two sessions of the laboratory. Half of each section of students completed the physical activity in the first week, while the other half completed the virtual activity. In the second week, the students switched activities, with those who had completed the physical activity now performing the virtual and those who had completed the virtual activity now performing the physical.

At the end of the second week, the students completed the survey about the usefulness of the physical and virtual experiments in various contexts. The contexts, concepts and pulley setups were the same as in the COPF09 study, as described in Table 4.8 above. In the COPF09 study, students were asked to choose between options representing the physical experiment, the virtual experiment and “both equally helpful”. A large percentage of students chose the “both equally helpful” option and their responses indicated they thought this option meant they would get to use both sets of data. To make the intent of this option more clear, it was changed to read “either would be equally helpful.”

Additionally, students were asked to respond to two additional questions based on the Wrap Up Questions used in the COPF09 study. Students were asked to explain which manipulative better supported their learning and which manipulative they found more trustworthy. The survey used in the PWS10 study is included in Appendix L.

#### *4.2.4.2 Research Question Addressed*

This study addresses Research Question 3, which focuses on students’ views of the physical and virtual data. Specifically, it builds on the results of the surveys used in the CoPF09 studies. Since students seemed to misinterpret the option “both equally helpful” on the survey used in the previous study, this option was rephrased and the survey was repeated in the PWS10 study.

## 4.3 Inclined Plane Studies

Three studies were conducted to explore how students’ learning about the physics concepts related to inclined planes was influenced by the use of physical and virtual manipulatives. The studies involved different groups of student participants, different formats, and different variations of the inclined plane curriculum. Each is described in detail below.

### *4.3.1 Inclined Plane Study #1: PWS09*

The CoMPASS inclined plane curriculum was used in the Physical World laboratory in the Spring 2009 semester. This is the same class of students used in Pulley Study #1, PWS09. In this section, I describe the study design, curriculum and tests used in the Physical World Spring 2009 (PWS09) implementation.

#### *4.3.1.1 Study Design*

As in the PWS09 pulley study, the Physical World laboratory had five sections, which met for two hours each. Each section was led by one of three teaching assistants, and at least one researcher was present during the implementation to help answer students' questions. The inclined plane curriculum was intended to involve three activities, which involved separately changing the length, height and surface of the ramp. Due to time constraints, the students were only able to complete two of the three activities. In addition, students used either physical or virtual manipulatives to complete the activities. The details of each sections' conditions are summarized in Table 4.11 below.

**Table 4.11 Physical World Spring 2009 Section Description for Inclined Plane Study**

| **Section** | **N** | **Manipulatives** | **Experiments** |
|---|---|---|---|
| A | 29 | Physical | Length/Height |
| B | 37 | Virtual | Length/Height |
| C | 23 | Physical | Length/Friction |
| D | 31 | Physical | Length/Friction |
| E | 30 | Virtual | Length/Friction |

Students took a pre-test before beginning the instruction and a post-test after completing the activities. They recorded data and responded to worksheet questions during the activities. The worksheets and tests are described in the following sections. This design allows for comparison of how students learned about length and height or length and friction using the physical and virtual manipulatives.

#### *4.3.1.2 Curriculum*

The worksheets from the PWS09 inclined plane implementation are included in Appendix M. The worksheets contained all three experiments (length, height and friction) because the initial intent was for students to complete all three experiments. Due to time constraints, students were only able to complete two of the three experiments. Students were instructed to cross out the pages that they were to skip.

All students began by reading the "Inclined Plane Challenge", which gave them the task of discovering the best way to use a ramp to lift a pool table into a van. Next, students completed the "Anticipation Guide", which asked them to respond "agree", "disagree" or "don't know" to several statements about inclined planes. Then, they were asked to write down anything they knew about inclined planes in the "Inclined Plane Brainstorming" section. Next, students made predictions about the best length and surface to move the pool table into the van, how height would affect the work needed, and how their answers would be affected by a ramp with no friction. Students then discussed their predictions with their group members and developed a list of questions to guide their research about inclined planes on the CoMPASS hypertext system. Next, students used the hypertext system to explore some of the science concepts related to inclined planes.

After using the CoMPASS website, students completed the activities. Each laboratory section completed the activities described in Table 4.11 above, using either physical or virtual equipment to do experiments on length and height or length and friction. The equipment used in the physical experiment is shown in Figure 4.4. Students using the physical equipment had to build the ramps by hand and use a spring scale to measure the force. Different versions of the simulation were used for different experiments. The simulation shown in Figure 4.5 below was used for the length and friction experiments. Students using the simulation moved the sliders in the "Experiment Set Up" section to create ramps and applied the force with the slider in the "Controls" section. This version of the simulation did not perform any calculations for the students. The simulation shown in Figure 4.6 below was used for the height experiment. The ramps were constructed and the force was applied in the same way as the previous simulation. However, this version of the simulation calculated and displayed work, potential energy, kinetic energy and total energy.

Students using physical or virtual equipment recorded much of the same data, including the distance the object moved, force, work, ideal mechanical advantage, actual mechanical advantage, friction (zero/low/high) and potential energy. In the length experiment, students using physical equipment tested a vertical lift; the vertical lift could not be reproduced using the current version of the simulation. In the simulation, students could create a frictionless ramp; students using physical equipment could only test wood on wood and wood on sandpaper surfaces.

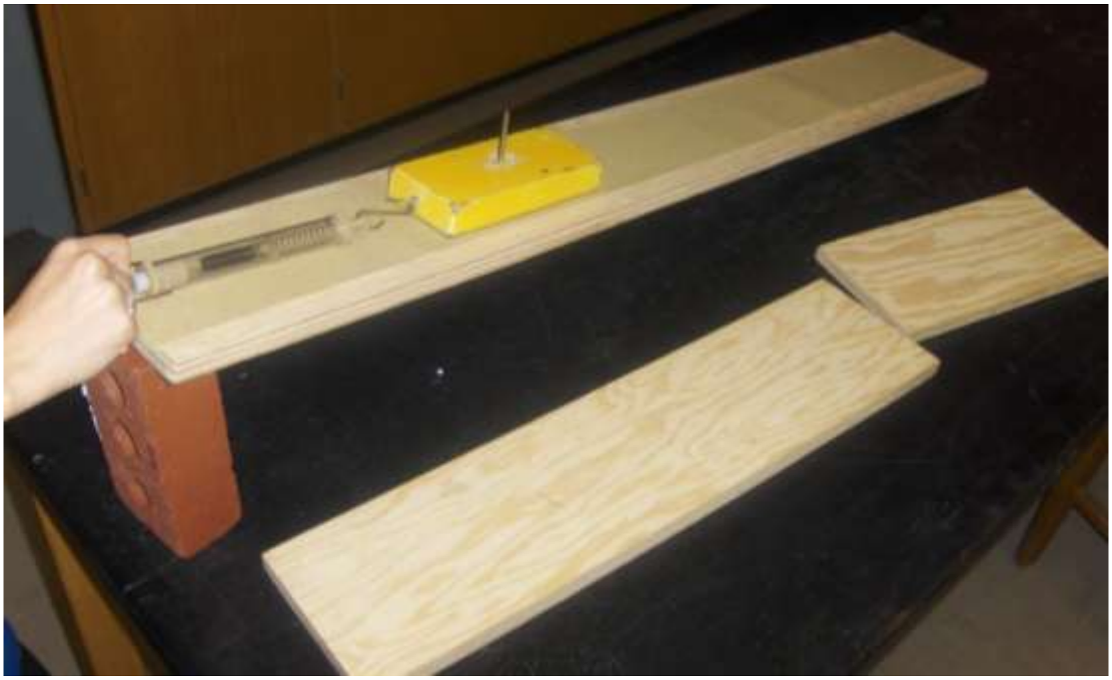
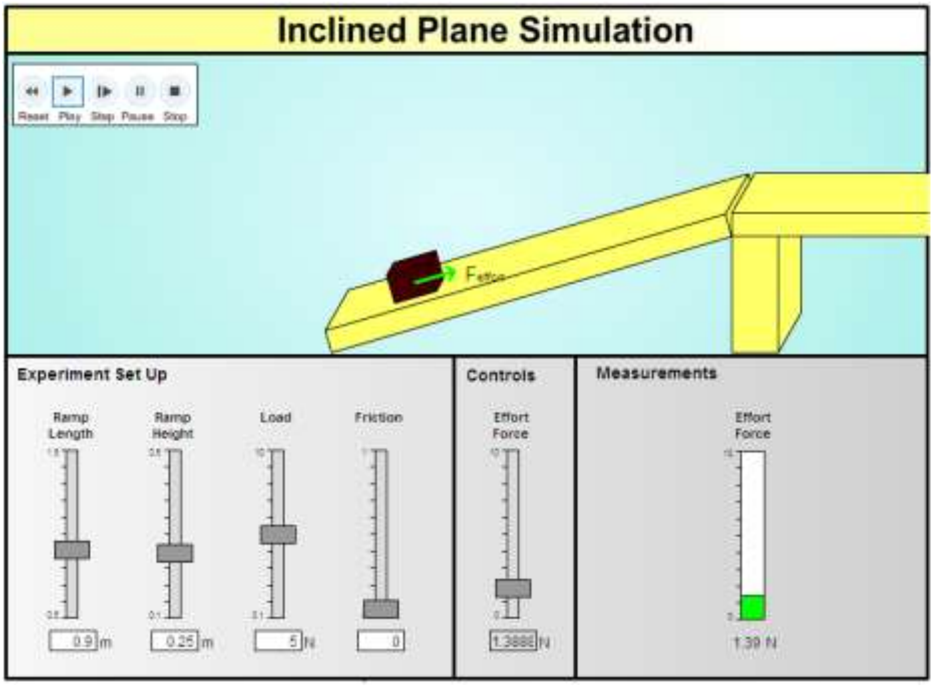
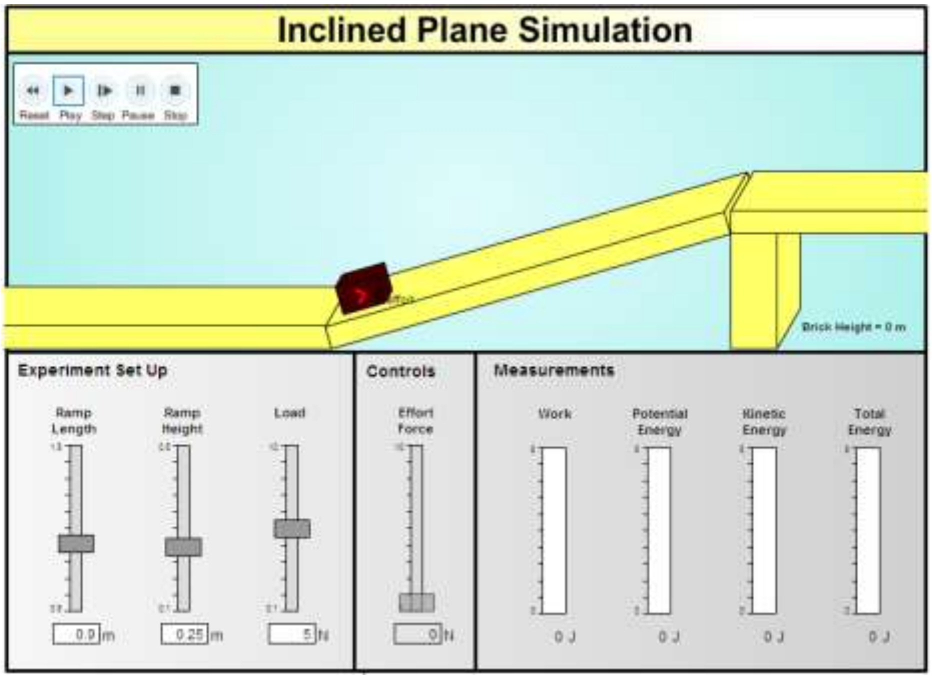


**Figure 4.4 Incline plane physical manipulatives.**



Ramp Length 0.9 m
Ramp Height 0.25 m
Load 5 N
Friction 0
Effort Force 1.3888 N
Effort Force 1.39 N

**Figure 4.5 PWS09 inclined plane simulation for length & friction experiments.**



Ramp Length 0.9 m
Ramp Height 0.25 m
Load 5 N
Effort Force 0 N
Work 0 J
Potential Energy 0 J
Kinetic Energy 0 J
Total Energy 0 J

**Figure 4.6 PWS09 inclined plane simulation for height experiment.**

After completing the experiments, students answered analysis questions. These questions varied by experiment and manipulative and are discussed in the following section. Then, students responded to the initial challenge by describing the best way to use a ramp to move the pool table into the van. Students who had used the simulation also responded to a question about how the simulation's conditions differed from those they would encounter with a real-life ramp and pool table.

#### *4.3.1.3 Assessment of Student Learning*

Students' worksheets included analysis questions that were used to examine what students learned by performing the physical and virtual experiments. See the PWS09 inclined plane worksheets in Appendix M for the analysis questions as they were presented to students. Students answered different questions based on the experiments they performed and the manipulatives they used to perform those experiments. The questions are reproduced in Table 4.12 below, which includes information about when each question was asked.

### Table 4.12 PWS09 Inclined Plane Worksheet Questions

| **Experiment** | **Question** | **V** | **P** |
|---|---|---|---|
| Length | Based on your data, when you **increase the length** of the ramp, how does it affect the **effort force** needed to move the pool table up the ramp (for a given height)? | X | X |
| Length | Based on your data, when you **increase the length** of the ramp, how does it affect the **work** needed to move the pool table up the ramp (for a given height)? | X | X |
| Length | Based on your data, when you **increase the length** of the ramp, how does it affect the **Ideal Mechanical Advantage** (for a given height)? | X | X |
| Length | Based on your data, when you **increase the length** of the ramp, how does it affect the **Actual Mechanical Advantage** (for a given height)? | X | X |
| Length | What do you think is the **effort force** needed to lift the pool table into the van without the use of a ramp? |  | X |
| Length | What do you think is the **work** needed to lift the pool table into the van without the use of a ramp? |  | X |
| Height | Based on your data, when you **increase the height** of the ramp, how does it affect the **effort force** needed to pull the block up the ramp (for the same length)? | X | X |
| Height | Based on your data, when you **increase the height** of the ramp, how does it affect the **work** needed to pull the block up the ramp (for the same length)? | X | X |
| Height | Based on your data, how does **work** compare to **potential energy**? | X | X |
| Friction | Based on your data, when you **increase friction**, how does it affect the **effort force** needed to pull the block up the ramp? | X | X |
| Friction | Based on your data, when you **increase friction**, how does it affect the **work** needed to pull the block up the ramp? | X | X |
| Friction | Based on your data, when you **increase friction**, how does it affect the **ideal mechanical advantage**? | X | X |
| Friction | Based on your data, when you **increase friction**, how does it affect the **actual mechanical advantage**? | X | X |
| Friction | Based on your data, how does the relationship between **Ideal MA** and **Actual MA** depend on friction? | X | X |
| Friction | Predict what would be the relationship between **Ideal MA** and **Actual MA** if the board were **frictionless**? | X |  |
| Friction | Based on your data, how does the relationship between **work** and **potential energy** depend on friction? | X |  |
| Friction | Predict what would be the relationship between **work** and **potential energy** if the board were **frictionless**? | X |  |

As shown in Table 4.12 above, additional questions were asked of the students who used the simulation in the length experiment and the students who used the physical equipment in the friction experiment. These questions were added to explore whether students could reason about the experiments that they could not perform with their given manipulative. Specifically, the inclined plane simulation did not allow students to test a vertical lift, so they were asked to speculate about the force and work that would be required to lift the block without the use of a ramp. The physical equipment did not allow students to test a frictionless surface, so students were asked to speculate about the relationship between ideal and actual mechanical advantage as well as work and potential energy for a frictionless board.

The test used in this study is included in Appendix N. The same test was used for the pre-test and the post-test. The test consisted of sixteen multiple-choice questions. One question asked students to explain their reasoning. Table 4.13 below summarizes the format of each question and the concept and inclined plane properties tested.

**Table 4.13 PWS09 Test Question Breakdown**

| Q# | Format | Main Physics Concept | Inclined Planes |
|---|---|---|---|
| 1 | Multiple-choice | Force | Different length, same height |
| 2 | Multiple-choice | Force | Ramp; Lifting |
| 3 | Multiple-choice | Force | Same length, different height |
| 4 | Multiple-choice | Force | Smooth surface; Rough surface |
| 5 | Multiple-choice | Force | Different length and height (proportional) |
| 6a* | Multiple-choice | Force | Different length, same height |
| 6b* | Multiple-choice | Work | Different length, same height |
| 7 | Multiple-choice | Work | Ramp; Lifting |
| 8 | Multiple-choice | Work | Smooth surface; Rough surface |
| 9 | Multiple-choice | Work | Same length, different height |
| 10 | Multiple-choice | Mechanical advantage | Different length, same height |
| 11 | Multiple-choice | Mechanical advantage | Different length, same height |
| 12 | Multiple-choice | Potential energy | Different length, same height |
| 13 | Multiple-choice | Potential energy | Same length, different height |
| 14 | Multiple-choice | Work/potential energy | Frictionless ramp |
| 15 | Multiple-choice | Ideal MA/Actual MA | Not specified |

#### *4.3.1.4 Research Questions Addressed*

This study addresses Research Question 1 (RQ1), which focuses on students' conceptual learning. Since students only used one type of equipment, physical or virtual, this study can only address what students learn from performing the physical and virtual experiments. Students' responses to the worksheet questions and their performance on the post-test were used to address this question.

### *4.3.2 Inclined Plane Study #2: PWF09*

The CoMPASS inclined plane curriculum was used in the Physical World laboratory in the Fall 2009 semester. This is the same class of students used in Pulley Study #2, PWF09. Changes were made to both the curriculum and the study design for the Physical World Fall 2009 (PWF09) inclined plane study to better address the research questions.

#### *4.3.2.1 Study Design*

As in the PWF09 pulley study, the Physical World laboratory had four sections, which met for two hours each. Each section was led by one of two teaching assistants and at least one researcher was present during the implementation to help answer students' questions. Unlike the PWS09 inclined plane study, in the PWF09 study students performed experiments using both physical and virtual manipulatives. The details of each section's conditions are summarized in Table 4.14 below.

**Table 4.14 Physical World Fall 2009 Section Descriptions**

| Section | N | Manipulatives |
|---|---|---|
| A | 26 | Virtual-Physical |
| B | 27 | Physical-Virtual |
| C | 31 | Virtual-Physical |
| D | 26 | Physical-Virtual |

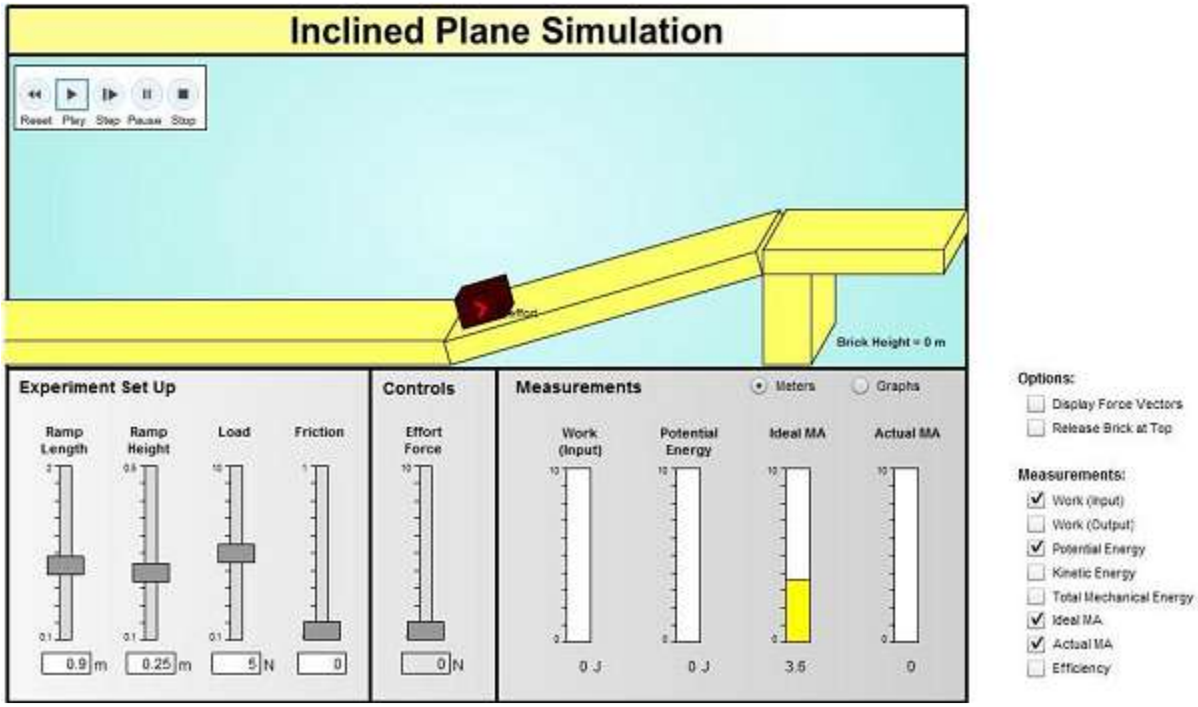
Students took a pre-test before beginning the instruction, a mid-test after completing the first set of experiments, and a post-test after completing the second set. They recorded data and responded to worksheet questions during each set of activities. The tests and worksheet questions are described in the following sections.

This design allows for several comparisons. The effectiveness of the physical and virtual activities alone can be assessed by comparing mid-test scores and students' responses to the first set of worksheet questions. The effectiveness of the physical-virtual and virtual-physical sequences can be assessed by comparing post-test scores and students' responses to the second set of worksheet questions.  The added benefit of completing the second activity can be assessed by comparing students' mid-test scores to their post-test scores.

#### *4.3.2.2 Curriculum*

The worksheets from the PWF09 inclined plane study are included in Appendix O. Changes were made from the PWS09 worksheets to alleviate the time constraints and better address the research questions.  As in the PWS09 study, students began by reading the "Inclined Plane Challenge" and responding to the "Anticipation Guide", brainstorming, and prediction prompts.  Students then discussed their predictions with their group members, developed a list of questions to guide their exploration in the CoMPASS hypertext system, and explored some of the science concepts related to inclined planes in the hypertext system.

After using the website, students completed the activities.  Rather than separate length, height and friction experiments as in the PWS09 study, students conducted one set of experiments and then answered analysis questions about how length, height and surface affected factors like force and work.  The same physical equipment was used as in the PWS09 study and is shown in Figure 4.4 above.  However, the simulation was changed, as shown in Figure 4.7 below, to give students more control of the virtual experiment.  Using this version of the simulation, students could choose which measurements to make and display.  Whereas students could previously only measure force, work, potential energy, kinetic energy and total energy, they could now also choose between work (input), work (output), ideal mechanical advantage, actual mechanical advantage and efficiency.  Students were encouraged to view the measurements for work (input), potential energy, ideal mechanical advantage and actual mechanical advantage, as shown in Figure 4.7 below.



Brick Height = 0 m

Ramp Length 0.9 m

Ramp Height 0.25 m

Load 5 N

Friction 0

Effort Force 0 N

● Meters ○ Graphs

Work (Input) 0 J

Potential Energy 0 J

Ideal MA 3.5

Actual MA 0

☐ Display Force Vectors

☐ Release Brick at Top

☑ Work (Input)

☐ Work (Output)

☑ Potential Energy

☐ Kinetic Energy

☐ Total Mechanical Energy

☑ Ideal MA

☑ Actual MA

☐ Efficiency

**Figure 4.7 PWF09 inclined plane simulation.**

Students using the physical and virtual manipulatives recorded the same data, including distance moved, height of van, friction, effort force, work (input), potential energy (at top of ramp), ideal mechanical advantage and actual mechanical advantage. However, when students used the physical equipment they had to calculate work, potential energy and mechanical advantage, while those quantities were reported in the simulation. In addition, when students used the simulation they were instructed to complete a “zero friction” trial, which was not possible using the physical equipment.

Students answered the same set of worksheet questions after both experiments, which are described in the following section. After completing the second activity, students responded to the initial challenge by describing the best way to use a ramp to move a pool table into a van. Students also responded to summary questions about how the two experiments’ conditions differed from a real-life ramp and pool table.

### *4.3.2.3 Assessment of Student Learning*

Students’ worksheets included analysis questions that were used to examine what students learned by performing the physical and virtual experiments. See the PWF09 inclined plane worksheets in Appendix O for the questions as they were presented to students. Students answered the same set of analysis questions after performing both sets of experiments. The questions are reproduced in Table 4.15 below.

**Table 4.15 PWF09 Inclined Plane Worksheet Questions**

| **Q#** | **Question** |
|---|---|
| WQ1 | How does the *effort force* needed to move the load change if the:<br>• *length* of ramp **increases**?<br>• *height* of the ramp **increases**?<br>• *surface* of the ramp gets **rougher**? |
| WQ2 | How does the *work (input*) needed to move the load change if the:<br>• *length* of ramp **increases**?<br>• *height* of the ramp **increases**?<br>• *surface* of the ramp gets **rougher**? |
| WQ3 | How does the *potential energy* of the load at the top of the ramp change if the:<br>• *length* of ramp **increases**?<br>• *height* of the ramp **increases**?<br>• *surface* of the ramp gets **rougher**? |
| WQ4 | Below you are asked to *compare work (input)* and *potential energy* in different conditions.<br>• How does the *work (input)* and *potential energy* compare when these **is friction**?<br>• How does the relationship between *work (input)* and *potential energy* change as the surface gets **smoother**?<br>• How does *work (input)* and *potential energy* compare when there is **no friction**? |
| WQ5 | How does the *ideal mechanical advantage* change if the:<br>• *length* of ramp **increases**?<br>• *height* of the ramp **increases**?<br>• *surface* of the ramp gets **rougher**? |
| WQ6 | How does the *actual mechanical advantage* change if the:<br>• *length* of ramp **increases**?<br>• *height* of the ramp **increases**?<br>• *surface* of the ramp gets **rougher**? |

The test used in this study is included in Appendix P. The same test was used for the pre-test, mid-test and post-test. The questions are summarized in Table 4.16 below. An asterisk is used to indicate new questions added since the PWS09 implementation. A plus sign is used in the “Format” column to indicate questions that asked students to explain their reasoning. The question number of the PWS09 test is indicated in parentheses.

**Table 4.16 PWF09 Inclined Plane Test Breakdown**

| Q# | Format | Main Physics Concept | Inclined Planes |
|---|---|---|---|
| 1 (1) | Multiple-choice | Force | Different length, same height |
| 2 (2) | Multiple-choice | Force | Ramp; Lifting |
| 4 (3) | Multiple-choice | Force | Same length, different height |
| 5 (4) | Multiple-choice | Force | Smooth surface; Rough surface |
| 6 (5) | Multiple-choice | Force | Different length and height (proportional) |
| 8a1 (6a) | Multiple-choice | Force+ | Different length, same height |
| 8b2 (6b) | Multiple-choice | Work+ | Different length, same height |
| 9* | Calculation | Work | |
| 10 (7) | Multiple-choice | Work | Ramp; Lifting |
| 11 (8) | Multiple-choice | Work | Smooth surface; Rough surface |
| 12 (9) | Multiple-choice | Work+ | Same length, different height |
| 13* | Multiple-choice | Work | Three ramps: same length, different height |
| 14 (11) | Multiple-choice | Mechanical advantage+ | Different length, same height |
| 15* | Multiple-choice | Mechanical advantage+ | Different length and height (proportional) |
| 16 (10) | Multiple-choice | Mechanical advantage | Different length, same height |
| 17 (13) | Multiple-choice | Potential energy | Same length, different height |
| 18 (12) | Multiple-choice | Potential energy | Different length, same height |
| 19* | Multiple-choice | Work/potential energy | Smooth surface |
| 20* | Multiple-choice | Work/potential energy | Rough surface |

Questions were added or removed from the PWS09 test to better align the pulley and inclined plane tests. The numbering was altered so that questions with the same number on the pulley and inclined plane tests were parallel. Question 14 from the PWS09 inclined plane test was rephrased as Question 19 on the PWF09 test. Question 15 from the PWS09 test was removed because there was no parallel question on the pulley test.

#### *4.3.2.4 Research Questions Addressed*

This study addresses Research Question 1 (RQ1), which focuses on students' conceptual learning. The relevant data to address the specific questions within RQ1 are summarized in Table 4.17 below.

**Table 4.17 Research Questions Addressed by PWF09 Inclined Plane Study**

| Research Question | Relevant Data |
|---|---|
| What do students learn from the physical activities, and what do they learn from the virtual activities? | Mid-test scores; First set of worksheet questions |
| When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity? | Mid-test and post-test scores within the same sequence |
| When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other?” | Post-test scores; Second set of worksheet questions |

### *4.3.3 Inclined Plane Study #3: Interviews*

Interviews were conducted using the CoMPASS materials with students enrolled in General Physics II in the Fall 2009 semester. Below I describe the structure and purpose of the interviews.

#### *4.3.3.1 Interview Structure*

Semi-structured teaching/learning interviews (Engelhardt *et al*., 2003) were used to explore how students used the physical and virtual manipulatives to build their understanding about the science concepts related to inclined planes. Eleven interviews were conducted. The physical equipment was used in five interviews, and the computer simulation was used in six interviews. The interview protocol is included in Appendix Q. The same protocol was used for all interviews, but the follow-up questions differed for each student. Each interview took about two hours.

To begin the interview, students were presented with a challenge similar to that used in the classroom studies. For the interviews, the challenge stated, “You work for a moving company and your job is to advise people about ramps they can use to move their stuff into a moving truck. As part of your training, you need to come up with a set of guiding rules for advising customers. So, your challenge here is to develop a set of guiding rules for advising customers about ramps.” The challenge was altered from that used in the class implementations to be more difficult, so as to encourage students to use the CoMPASS hypertext system and physical manipulatives or computer simulation to develop their understanding.

After presenting the challenge, the interviewer asked a series of questions designed to elicit the students' current understanding of the science concepts related to inclined planes. This was similar to the brainstorming and prediction phases of the class study worksheets. Next, similar to the worksheets, students were asked to develop a list of questions they would ask an expert to help them come up with the guiding rules for advising customers about ramps. Students then used the CoMPASS hypertext system to explore the science concepts related to inclined planes.

Next, students were encouraged to use the manipulatives, either the physical equipment or the computer simulation, to explore the ideas they had brought up during the initial phase of the interview. The physical equipment and simulation used were the same as in the PWF09 inclined plane study, shown in Figures 4.4 and 4.7 above. After the open exploration, students were asked five "mini-challenge" questions designed to get them to explore certain physics concepts. The questions and targeted concepts are summarized in Table 4.18 below.

**Table 4.18 "Mini-challenge" Questions and Target Concepts for Inclined Plane Interviews**

| "Mini-challenge" Question | Target Concept |
|---|---|
| Your company uses a motor to pull objects up a ramp. A rope connects the motor and object being moved. If you were given a moving truck and a rope that has a maximum force tolerance, how can you figure out which ramps to use? | Force decreases as ramp slope decreases |
| Given several different moving trucks, smooth ramps and a given load, how can you predict how much the electric bill would be to move the object? | Energy used (electric bill) depends only on height for frictionless ramps; Work done is equal to change in potential energy |
| Given several different moving trucks, rough ramps and a given load, how can you predict how much the electric bill would be? | Energy used (electric bill) depends on height and length for ramps with friction; Work done is more than change in potential energy |
| Given a specific truck, smooth ramps, and a rope with a certain force tolerance, how can you predict how much the electric bill will be with different length ramps? | Work done (electric bill) depends on the product of force and length |
| Suppose you had chosen a certain length for a certain height truck. On moving day, it turns out you have to use a truck that is twice as high. How could you quickly predict the best length of ramp to use? | Load to effort force ratio depends on steepness of ramp (mechanical advantage) |

After using the equipment to explore the “mini-challenge questions”, students were asked to summarize their ideas about the best way to use ramps to meet the customers’ needs.  In addition, students were asked how the manipulatives they used were different from the equipment they would use in the real world and asked about their preferences for using physical or virtual equipment to perform the experiments.

#### *4.3.3.2 Research Questions Addressed*

The inclined plane interviews were used to address Research Question 3, which focuses on how students use the physical and virtual equipment to build their understanding. Specifically, the interviews were analyzed through the lens of dynamic transfer, described in Section 2.5.2.4 above.  Because the environment plays an important role in supporting dynamic transfer, the environments created and support offered by the physical equipment and computer simulation during the interviews were compared.

## 4.4 Roadmap to the Dissertation

The remaining chapters present the results of the studies described above to address the research questions.  The Table 4.19 below outlines the research question (RQ) and studies addressed in each chapter.  RQ1 focuses on students’ conceptual understanding, RQ2 focuses on how students learn, and RQ3 focuses on students’ views of the physical and virtual experiments.

**Table 4.19 Roadmap to the Dissertation**

| Chapter | Description | Research Question | Studies |
|---|---|---|---|
| 5 | Pulley Worksheet Analysis | 1) What do students learn from the physical activities, and what do they learn from the virtual activities? When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity? When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other? | Pulley Studies: PWS09, PWF09, CoPF09 |
| 6 | Pulley Test Analysis | | Pulley Studies: PWS09, PWF09, CoPF09 |
| 7 | Inclined Plane Worksheet Analysis | | Inclined Plane Studies: PWS09, PWF09 |
| 8 | Inclined Plane Test Analysis | | Inclined Plane Studies: PWS09, PWF09 |
| 9 | Dynamic Transfer Analysis | 2) Do the environments created by the physical and virtual manipulatives offer different support for dynamic transfer? What features of each environment create the support? Can the support offered by one environment be recreated in the other? | Inclined Plane Interview Study |
| 10 | Survey Analysis | 3) Do students view the information from physical and virtual manipulatives differently? Is there evidence that different epistemic resources are activated by the two contexts? | Pulley Studies: CoPF09, PWS10 |

# CHAPTER 5 - Pulley Worksheet Analysis

In this chapter, I discuss students' responses to the worksheet questions in the pulley studies. For each study, I describe the questions students were asked, the physically correct responses to those questions, and the range and frequency of responses provided by students. Then, I present the results of the chi-square test for independence, which helps to explain whether the responses students provided differed based on the manipulative they used to perform the experiment. In Chapter 6, I present the analysis of students' performance on the conceptual tests, which provides evidence that students did learn about the physics of pulleys while working through the activities. Together these results help to address Research Question 1, specifically the questions:

- What do students learn from the physical activities, and what do they learn from the virtual activities?
- When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other?

## 5.1 Pulley Study #1: Physical World Spring 2009 (PWS09)

In the Physical World Spring 2009 (PWS09) study, students used both the physical and virtual manipulatives to test several pulley setups (single fixed pulley, single movable pulley, single compound pulley, and double compound pulley). Some students (N=71) performed the physical experiment followed by the virtual experiment (PV sequence), while others (N=61) first performed the virtual experiment and then the physical experiment (VP sequence). For a more complete description of the study, see Section 4.2.1.

After performing experiments with each manipulative, students answered a set of analysis questions. In this section, I describe the questions and the categories of responses that emerged from the analysis. In addition, I present the results of the chi-square test for independence for two comparisons: responses provided after the first experiment in each sequence (which addresses whether students responded differently after performing only the physical or only the virtual experiment) and responses provided after the physical experiment in each sequence (which addresses whether the virtual activity influences how students interpret the data from the physical experiment). Fisher's exact test was used when expected cell counts were less than five. A significant result indicates that the responses from the PV and VP sequences represent two different populations. Because two comparisons were performed with the same data, the significance level (α) was reduced from 0.050 to 0.025 (Everitt, 1992). When a significant result was found, adjusted residuals were examined to determine which cells contributed to the significance. Adjusted residuals greater than 1.96 were taken to indicate significant cells (Haberman, 1973).

### *5.1.1 WQ1: Applied Force*

WQ1 asked, "Based on your data, which pulley setup required the **smallest effort (force)** to lift the load?" The students tested four pulley systems: single fixed, single movable, single compound and double compound. The physically correct response is that the double compound pulley requires the least applied force (of the pulley systems tested) because it has the most supporting strands. As shown in Figure 5.1 below, all students correctly identified the double compound system as the pulley setup that required the least force in both the physical and the virtual experiments. The labels in the graph refer to the treatment (physical-virtual: PV; virtual-physical: VP) and activity (physical: P; virtual: V) that the bar represents.

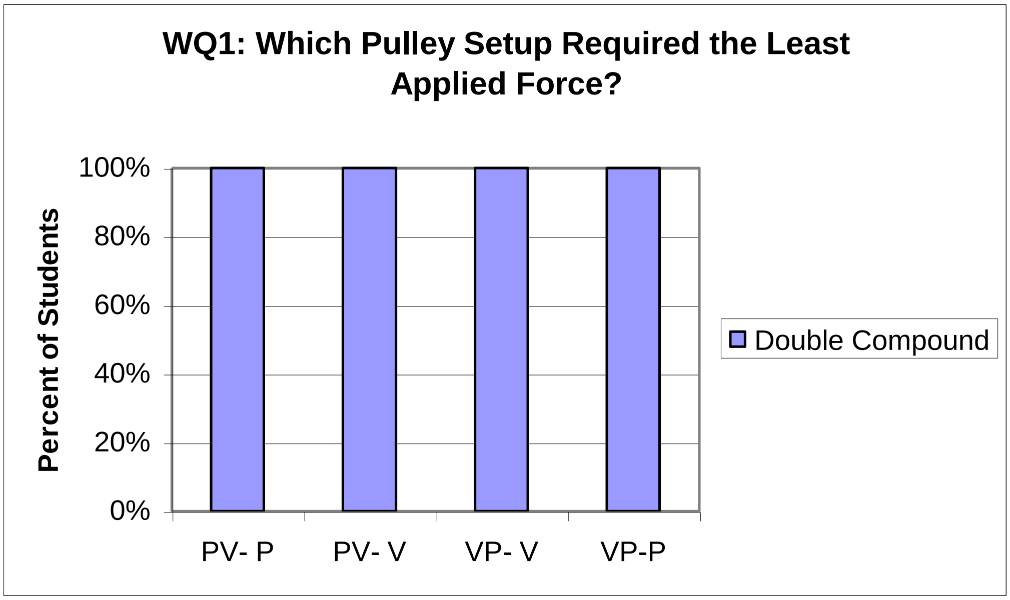


**Figure 5.1 PWS09 Worksheet Question 1 responses.**

The chi-square test for independence was not performed since all students in both sequences provided the same response. This result is not surprising as the double compound system required half as much force to lift the load as the single movable and single compound pulleys and one quarter as much force as the single fixed pulley. This difference should have been clear in both the physical and virtual experiments.

### *5.1.2 WQ2: Applied Force and Distance Pulled*

WQ2 asked, "Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?" The physically correct response is that when the distance the string is pulled to lift the object is increased, less applied force is required. Because the work needed to lift the same load to the same height is constant (under ideal conditions), the product of force and the distance over which the force is applied must be constant; if force is decreased, distance pulled must increase. The CoMPASS hypertext system refers to this idea as the "force-distance tradeoff."

As shown in Figure 5.2 below, the vast majority of students (about 90%) responded that the required force decreased as the distance pulled increased in each experiment. A small percentage (less than 10%) of students gave different answers. In the PV sequence, some of these students in responded either that the force did not change (about 5%) or increased as the distance pulled increased (less than 5%) in both the physical and virtual experiments. In the VP sequence, some of these students responded that the force increased as the distance pulled increased (less than 5%) in both the virtual and physical experiments.

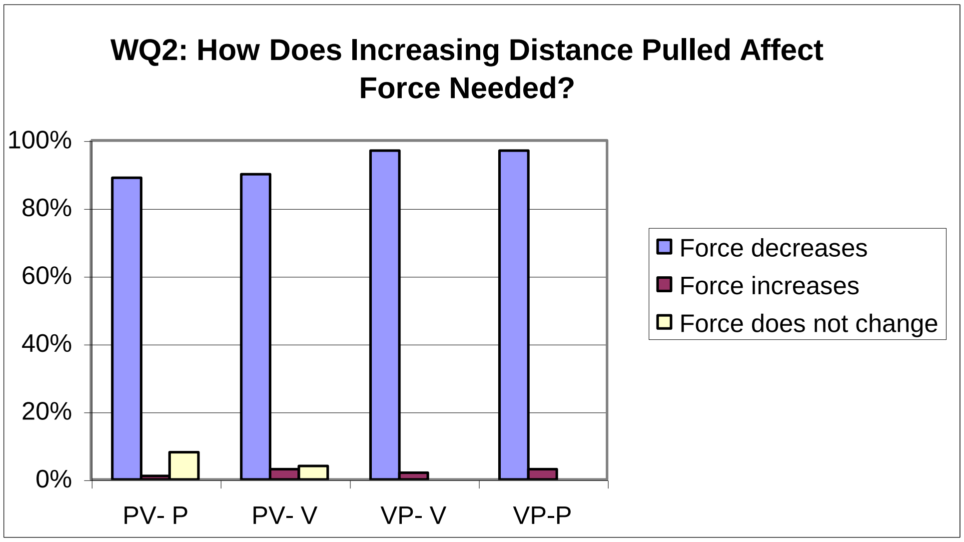


**Figure 5.2 PWS09 Worksheet Question 2 responses.**

The chi-square test for independence was performed with the categories “force decreased”, “force increased”, “force didn’t change” and “other.” For the responses provided after the first experiment in each sequence (physical experiment in the PV sequence and virtual experiment in the VP sequence), the two sequences were not significantly different, $\chi^2$(3, N=132)=6.0, p=.041. For the responses provided after the physical experiment in both sequences (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again not significantly different, $\chi^2$(3, N=132)=6.8, p=.031. It is perhaps surprising that students in the two treatments were equally successful on this question. In the physical experiment, students physically had to pull the rope a longer distance and could physically feel which system required less applied force. However, it appears the simulation was equally effective as the physical experiment in helping students to understand the relationship between force and distance in the context of pulleys.

### *5.1.3 WQ3: Distance Pulled and Distance Moved*

WQ3 asked, “Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?” As stated above, the double compound pulley required the smallest applied force to lift the load. Because the double compound pulley has four supporting strands, the applied force needed is one-fourth the weight of the object. Since the work required to lift the load remains constant when the pulley system is changed, the distance pulled (distance over which the force is applied) is four times greater than the distance the object is moved.

As shown in Figure 5.3 below, the majority of students responded either in general that the distance pulled was greater than the distance the object moved (about 50% in each sequence) or more specifically that the distance pulled was four times the distance the object moved (about 30% in each sequence). After the physical experiment in the PV sequence, a small number of students (6%) in the PV sequence responded that the distance pulled was three times the distance moved. This response likely reflects the trend students saw in the physical experiment since their results were affected by frictional effects and measurement error. A few students in both sequences (3%) responded that the distance pulled and the distance the object moved were about the same. This response occurred after the first experiment in each sequence (i.e. after the physical experiment in the PV sequence and after the virtual experiment in the VP sequence.) In addition, a few students (about 2%) responded that the distance pulled was less than the distance the object moved. This response occurred after both experiments in the VP sequence and after the physical experiment in the PV sequence. These responses represent incorrect interpretations of the data.

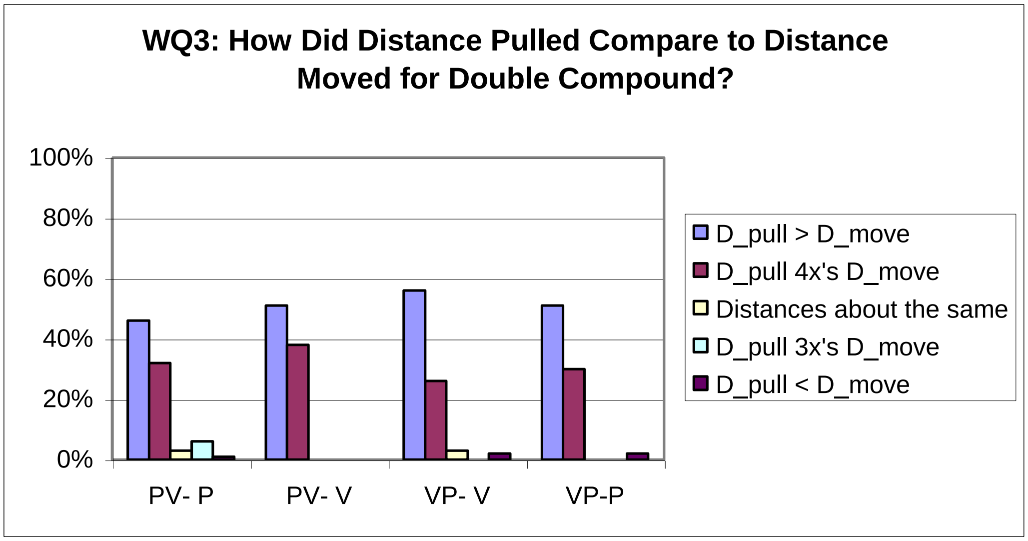


**Figure 5.3 PWS09 Worksheet Question 3 responses.**

The chi-square test for independence was performed with the categories “distance pulled greater than distance moved”, “distance pulled four times distance moved”, “distances pulled and moved about the same”, “distance pulled three times distance moved”, “distance pulled less than distance moved” and “other.” In the comparison between responses provided after the first experiment (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(5, N=132)=4.6, p=.467$. Similarly, in the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again not significantly different, $\chi^2(5, N=132)=5.6, p=.319$. As with WQ2, it is perhaps surprising that the physical and virtual manipulatives provided equal support for students’ understanding of distance since the physical experiment allowed students to physically experience the distances pulled and moved. However, it appears the support provided by the simulation was equally as effective as the kinesthetic experience.

### *5.1.4 WQ4: Work*

WQ4 asked, “Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?” In the activities, students were instructed to lift the same load to the same height with each pulley system. Thus, the work required to lift the load was the same across all pulley systems in the simulation. The work was very similar across the pulley systems in the physical experiment, although small fluctuations were observed due to frictional effects and measurement errors.

Students’ answers to this question varied based on the manipulative they used and the sequence in which they used the manipulatives, as shown in Figure 5.4 below. In both sequences, when students performed the experiment with the computer simulation, the vast majority (about 90%) of students responded that work was constant as the pulley system changed. In the PV sequence, when students performed the physical experiment, the majority (30%) of students responded that the work got easier as the pulley system got more complex, that the work changed (23%), or that the work increased (15%) as the pulley system got more complex. After the physical experiment in the PV sequence, a smaller percentage (22%) of students responded that the work was constant or nearly constant. On the other hand, when students in the VP sequence performed the physical experiment, the majority of students responded that the work was constant (39%). In addition, a larger percentage (20%) of students than in the PV sequence responded that the work was nearly constant. A smaller percentage

(23%) of students than in the PV sequence responded that the work got easier or changed as the pulley system got more complex. In general, for the physical experiment, students in the PV sequence appear to have focused on the fluctuations in work values, while the students in the VP sequence seemed to focus on the similarity in work values.

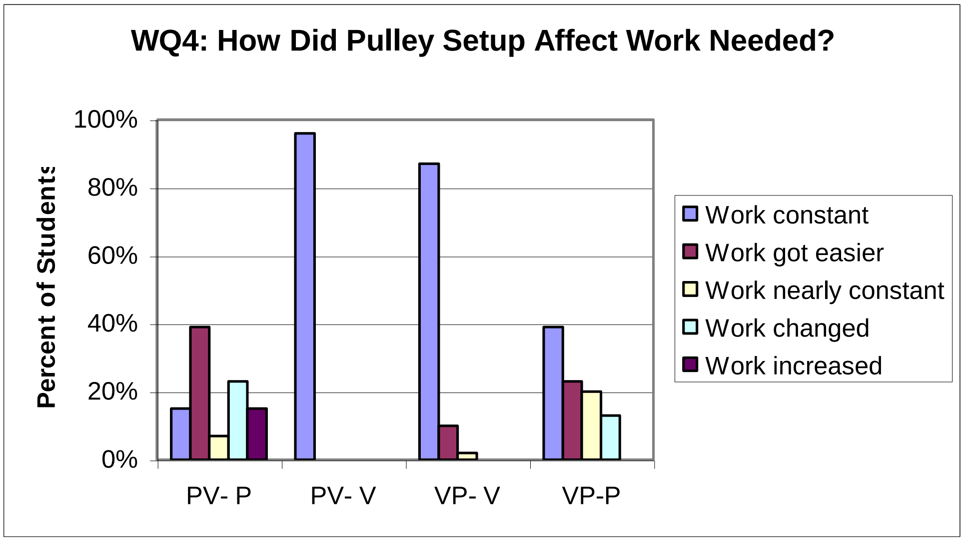


**Figure 5.4 PWS09 Worksheet Question 4 responses.**

The chi-square test for independence was performed with the categories "work stayed constant", "work got easier", "work stayed nearly constant", "work changed", "work increased" and "other." In the comparison between responses provided after the first experiment (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were significantly different, $\chi^2(5, N=132)=78.4$, $p<.001$. After performing only the virtual experiment, students were more likely to respond that work was constant when the pulley system changed than were students responding after performing only the physical experiment. Students who had performed only the physical experiment were more likely to provide a variety of responses, such as: work got easier; work was nearly constant; work changed; and work increased. Similarly, in the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again significantly different, $\chi^2(5, N=132)=28.5$, $p<.001$. In the PV sequence, students were more likely to respond that work got easier or increased, while in the VP sequence, students were more likely to respond that work was constant or nearly constant.

Overall, students in the VP sequence were more likely to describe the work as constant or nearly constant across pulley systems than were students in the PV sequence. In the VP sequence students are first presented with data from idealized (i.e. frictionless) conditions. Thus, the data clearly presents the idea that work does not depend on the pulley system. In the physical experiment, there are small variations in the work values between pulley systems due to frictional effects and measurement errors. Students in the VP sequence continued to discuss the similarity in work values in the physical experiment. Thus, it appears that performing the virtual experiment first may help students make more useful interpretations of the physical data. It is possible that presenting students with the generalized, non-friction case in the simulation followed by the specific, with-friction case in the physical experiment is a useful sequence.

### *5.1.5 WQ5: Work and Potential Energy*

WQ5 asked, "Based on your data, how does **work** compare to **potential energy** for a given pulley system?" Under ideal conditions, the work put into lifting the load is equal to the change in the load's potential energy. In the physical experiment, some energy is dissipated through friction so students likely observed the work to be slightly greater than the change in the load's potential energy.

As shown in Figure 5.5 below, students' responses to this question were dependent on the manipulative and sequence in which the manipulatives were used. In both sequences, when students used the computer simulation to perform the experiment, the majority of students (72% in the VP sequence and 93% in the PV sequence) responded that work was equal to potential energy. A small percentage of students gave alternative answers. However, when students used the physical equipment there was more variety in their responses. After the physical experiment in the PV sequence, the majority of students responded that the work changed while the potential energy remained constant (29%) or that the work was greater than the potential energy (20%). A smaller percentage of students responded the work was equal (14%) or nearly equal (13%) to the potential energy. Very few students responded either that the potential energy was greater than the work (6%) or that the potential energy and work were not related (7%). More students in the VP sequence than the PV sequence responded that the work and potential energy were the same (46%) or nearly the same (26%) after performing the physical experiment. A smaller percentage of students provided the alternative responses.

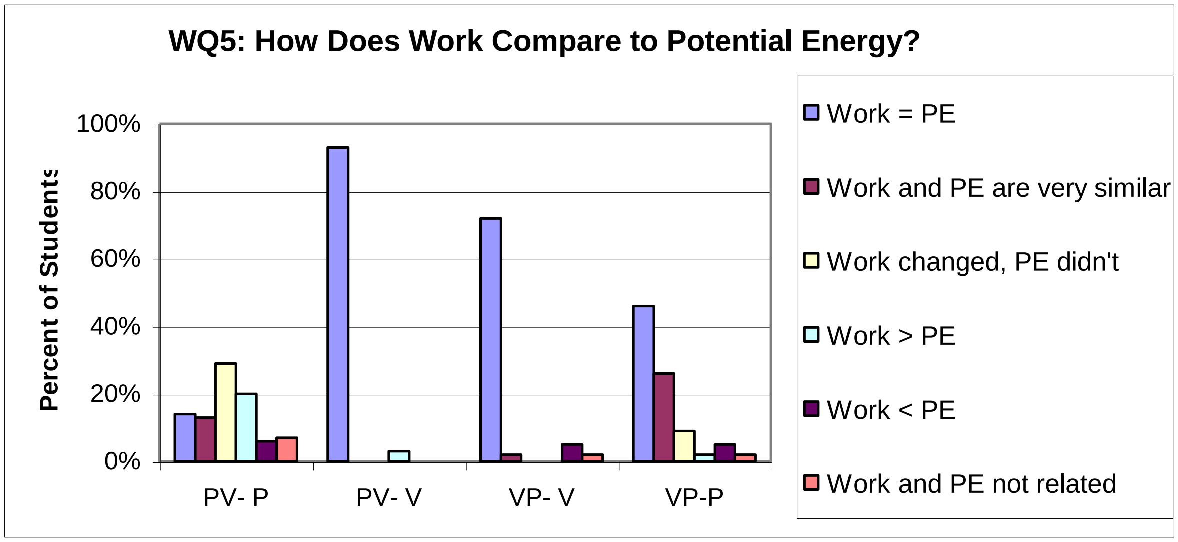


**Figure 5.5 PWS09 Worksheet Question 5 responses.**

The chi-square test for independence was performed with the categories "work equaled potential energy", "work and potential energy were similar", "work changed and potential energy stayed the same", "work was greater than potential energy", "work was less than potential energy", "work and potential energy are not related" and "other." In the comparison between responses provided after the first experiment (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were significantly different, $\chi^2(6, N=132)=73.8$, $p=<.001$. After performing only the virtual experiment, students were more likely to respond that work is equal to potential energy. On the other hand, after performing only the physical experiment, students were more likely to provide a variety of responses, such as: work and potential energy are similar; work changed and potential energy did not; and work is greater than potential energy. Similarly, in the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again significantly different, $\chi^2(6, N=132)=35.0$, $p<.001$. Students in the VP sequence were more likely to respond that work was equal or nearly equal to potential energy, while students in the PV sequence were more likely to respond that work changed and potential energy did not or that work was greater than potential energy.

Students' responses to WQ5 followed the same trend as WQ4. Again, this is not surprising because the computer simulation presented data from idealized (i.e. frictionless) conditions such that work and change in potential energy were exactly equal. In addition, the graphical representation in the simulation may support students in making comparisons between work and potential energy.

### *5.1.6 WQ6: Mechanical Advantage*

WQ6 asked, "Which pulley setup gave you the *greatest* **mechanical advantage**?" Mechanical advantage is a measure of how much the pulley system reduces the applied force necessary to lift the load. The actual mechanical advantage is calculated by dividing the weight of the load by the force needed to lift the load. Since tension is constant throughout the string or rope, each supporting strand pulls up on the load with a force equal to the applied force. Thus, the mechanical advantage can be estimated by counting the number of supporting strands in the pulley system. Under ideal conditions, the mechanical advantage is equal to the number of supporting strands.

As shown in Figure 5.6 below, nearly all students correctly identified the double compound pulley as the setup with the most mechanical advantage in both sequences. A few students (5%) in the VP sequence responded that the mechanical advantage was the same for all pulley setups. They provided this response for both the virtual and physical experiments. In the PV sequence, a few students (5%) identified an alternate pulley system as the system with the most mechanical advantage. They provided this response only for the virtual experiment.

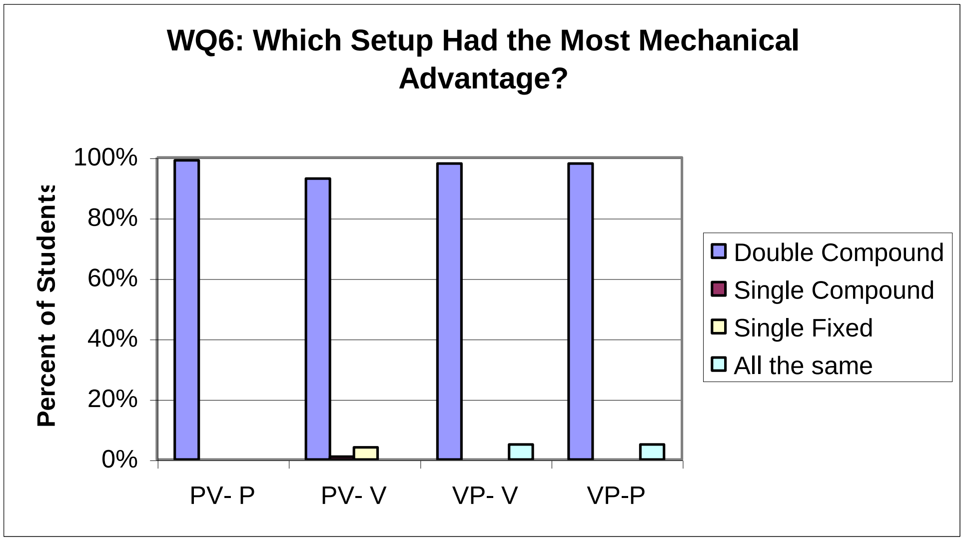


**Figure 5.6 PWS09 Worksheet Question 6 responses.**

The chi-square test for independence was performed with the categories “double compound” and “other pulley system.” In the comparison between responses provided after the first experiment (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(1, N=131)=4.7$, $p=.045$. Similarly, in the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were not significantly different, $\chi^2(1, N=131)=4.7$, $p=.045$. This is not surprising because the difference in mechanical advantage between the pulley systems was large and easily observable in both the physical and virtual experiments.

### *5.1.7 WQ7: Mechanical Advantage and Supporting Strands*

WQ7 asked, “Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?” As explained above, the mechanical advantage can be estimated by counting the number of supporting strands. Thus, the mechanical advantage increases when the number of supporting strands is increased.

As shown in Figure 5.7 below, the majority of students (more than 90%) in both sequences correctly responded that the mechanical advantage increased as the number of supporting strands increased. After the virtual experiment in the PV sequence, a few students (6%) responded that the mechanical advantage decreased as the number of supporting strands increased. Very few students (2%) provided this response after the virtual experiment in the VP sequence. In addition, a few students (less than 5%) in the VP sequence responded that the mechanical advantage remained constant after performing the virtual and physical experiments.

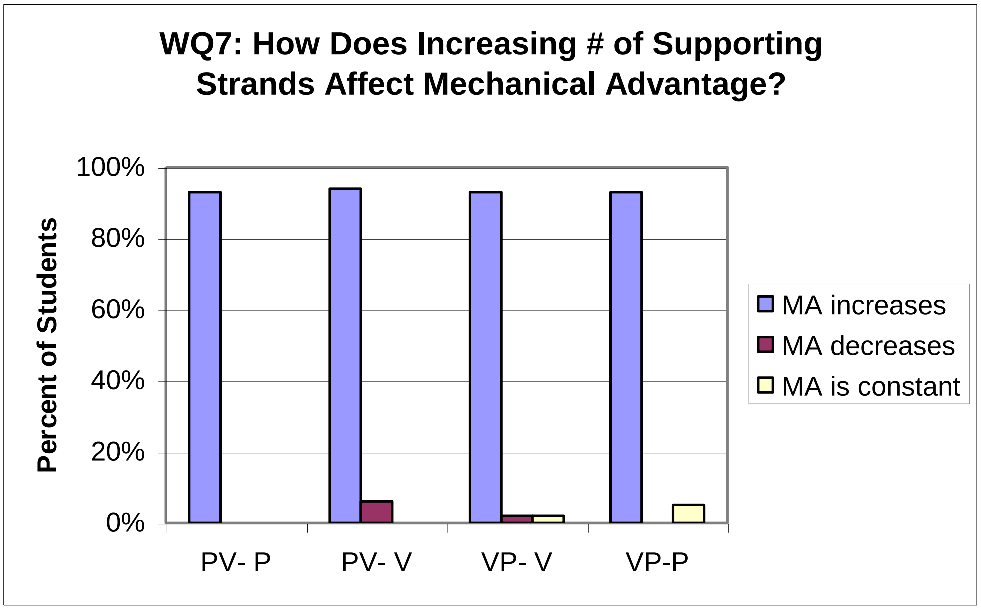


**Figure 5.7 PWS09 Worksheet Question 7 responses.**

The chi-square test for independence was performed with the categories “mechanical advantage increases”, “mechanical advantage decreases”, “mechanical advantage stays the same” and “other.” For the comparison between responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were significantly different, $\chi^2(3, N=131)=1.5$, $p=.910$. Similarly, in the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were not significantly different, $\chi^2(3, N=131)=4.3$, $p=.172$. This result is perhaps surprising since students have the kinesthetic experience of actually stringing the pulleys and creating the supporting strands in the physical experiment and do not have a similar experience in the virtual experiment. However, these results seem to indicate that the physical and virtual manipulatives equally supported students’ understanding of the relationship between supporting strands and mechanical advantage.

### *5.1.8 WQ8: Comparison of Physical and Virtual Experiment (Work and Potential Energy)*

WQ8 asked, “How does the relationship between **work** and **potential energy** in the *experiment* compare with the *simulation*?” Since the simulation has ideal conditions, the work needed to lift the load is exactly equal to the change in the object's potential energy. In the physical experiment, some work is dissipated through friction, and the work is slightly larger than the change in the load's potential energy. Thus, work and potential energy are equal in the simulation, but work is slightly greater than potential energy in the physical experiment.

As shown in Figure 5.8 below, the responses of students from both sequences fell in the same major categories and follow the same general trend. In the PV sequence, the majority of students (43%) responded that work and potential energy were the same in the simulation, but different in the physical experiment. The next most common response (given by 21% of students) was that work and potential energy had the same relationship in both the physical and virtual experiments. A few students (11%) responded that the relationship between work and potential energy was about the same in the two experiments, while a few others (7%) responded that the relationship was different. In the VP sequence, a nearly equal number of students responded that the relationship between work and potential energy was the same (25% of students) or nearly the same (25% of students) in the two experiments and that the work and potential energy were the same in the simulation, but different in the physical experiment (28% of students).

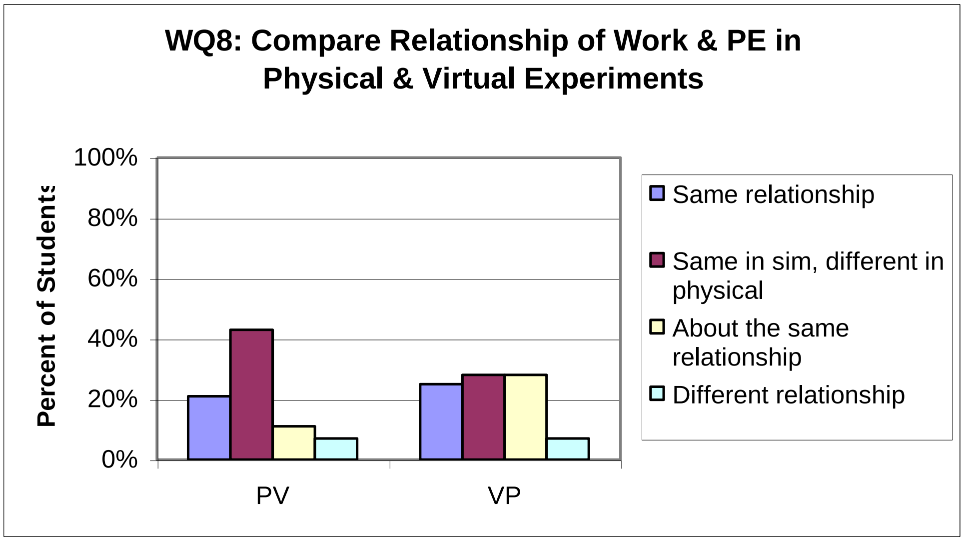


**Figure 5.8 PWS09 Worksheet Question 8 responses.**

The chi-square test for independence was performed with the categories "same relationship in physical experiment and simulation", "work and potential energy were the same in the simulation but different in the physical experiment", "about the same relationship in the physical experiment and simulation", "different relationship in the physical experiment and simulation", and "other." There was no statistically significant difference between the responses provided by students in the PV and VP sequences, $\chi^2(4, N=131)=7.1, p=.127$. This result is somewhat surprising since it appeared that the VP sequence helped students understand the relationship between work and potential energy better than the PV sequence did.

### *5.1.9 WQ9: Comparison of Physical and Virtual Experiments (Mechanical Advantage and Supporting Strands)*

WQ9 asked, "How does the relationship between **mechanical advantage** and the **number of supporting strands** in the *experiment* compare with the *simulation*?" Because the simulation has ideal conditions, the number of supporting strands is exactly equal to the mechanical advantage. In the physical experiment, the mechanical advantage differed slightly due to frictional effects and measurement errors.

As shown in Figure 5.9 below, students' responses in both sequences follow the same trend. The majority of students responded that the relationship between mechanical advantage and number of supporting strands was the same (about 50%) or nearly the same (about 25%) in both the physical and virtual experiments. Fewer students described the relationship, specifically that more supporting strands meant more mechanical advantage (about 20% in the PV sequence and about 10% in the VP sequence).

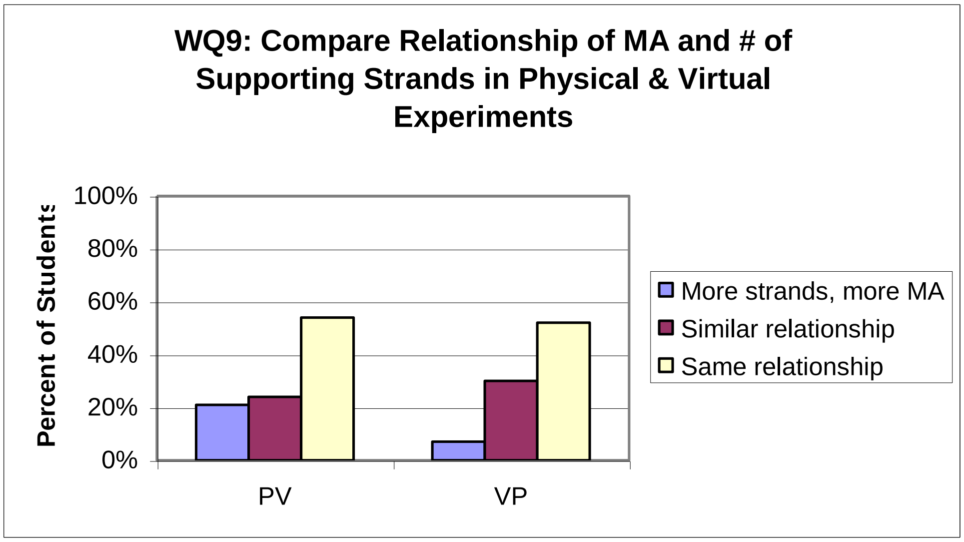


**Figure 5.9 PWS09 Worksheet Question 9 responses.**

The chi-square test for independence was performed with the categories “more supporting strands means more mechanical advantage”, “similar relationship in the physical experiment and simulation”, “same relationship in the physical experiment and simulation” and “other.” There was a statistically significant difference between the responses provided by students in the PV and VP sequences, $\chi^2(3, N=131)=13.7, p=.003$. Students in the PV sequence were more likely to respond that more supporting strands meant more mechanical advantage, while students in the VP sequence were more likely to provide an alternate response (“other”). The physical manipulatives provide less support than the virtual manipulative for making comparisons. For example, the simulation presents data in side-by-side bar graphs, which may help students make comparisons between quantities. It is possible that students in the PV sequence were more likely to describe mechanical advantage than to compare the physical and virtual experiments (as was asked in the question) because they received less support for making comparisons in their first activity.

### *5.1.10 Summary*

In the previous sections, I have presented students’ responses to the pulley analysis questions and the results of the chi-square test for independence on the responses provided in the PV and VP sequences for two specific contrasts. The first contrast was between the responses provided after the first experiment in each sequence (physical experiment in PV and virtual experiment in VP). This contrast addresses whether students responded to each question differently after using the physical or virtual manipulative. The second contrast was between the responses provided after the physical experiment in each sequence (first experiment in PV sequence and second experiment in VP sequence). This contrast addresses whether performing the virtual experiment before the physical experiment affects the way students interpret the data from the physical experiment. I chose this contrast because I believe it is of interest to physics instructors, who tend to place value on developing their students' ability to perform and analyze real-world experiments. Table 5.1 below summarizes the results of these contrasts. As discussed above, since two contrasts were performed the significance level was reduced from $\alpha=0.050$ to $\alpha=0.025$. Fisher's exact test was used for contrasts where expected counts in any category were less than 5 (which was all of the contrasts in this study).

## Table 5.1 Summary of PWS09 Worksheet Contrast Statistics

| | | **First Experiment** (PV physical responses compared to VP virtual responses) | | | **Physical Experiment** (PV physical responses compared to VP physical responses) | | |
|---|---|---|---|---|---|---|---|
| **Q#** | **Question Description** | $\chi^{2+}$ | **p**$^{++}$ | **V**$^{+++}$ | $\chi^{2+}$ | **p**$^{++}$ | **V**$^{+++}$ |
| 1 | Applied Force | Not performed | | | Not performed | | |
| 2 | Applied Force and Distance Pulled | $\chi^2(3, N=132) =6.0$ | .041 | .21 | $\chi^2(3, N=132) =6.8$ | .031 | .23 |
| 3 | Distance Pulled and Distance Moved | $\chi^2(5, N=132) =4.6$ | .467 | .19 | $\chi^2(5, N=132) =5.6$ | .319 | .21 |
| 4 | Work | $\chi^2(5, N=132) =78.4$ | **<.001** | .77 | $\chi^2(5, N=132) =28.5$ | **<.001** | .46 |
| 5 | Work and Potential Energy | $\chi^2(6, N=132) =73.8$ | **<.001** | .75 | $\chi^2(6, N=132) =35.0$ | **<.001** | .51 |
| 6 | Mechanical Advantage | $\chi^2(1, N=131) =4.7$ | .045 | .19 | $\chi^2(1, N=131) =4.7$ | .045 | .19 |
| 7 | Mechanical Advantage and Supporting Strands | $\chi^2(3, N=131) =1.5$ | .910 | .11 | $\chi^2(3, N=131) =4.5$ | .172 | .19 |
| | | (Only asked after final experiment in each sequence) | | | | | |
| 8 | Comparison of Physical and Virtual Experiments: Work and Potential Energy | $\chi^2(4, N=131) =7.1$ | .127 | .23 | | | |
| 9 | Comparison of Physical and Virtual Experiments: Mechanical Advantage and Supporting Strands | $\chi^2(3, N=131) =13.7$ | **.003** | .32 | | | |

$^{+}$The format is $\chi^2$(degrees of freedom, N) =chi-square statistics

$^{++}$Significance value

$^{+++}$Effect size

The chi-square test for independence indicated that the PV and VP sequences represented two different populations for Questions 4, 5 and 9. For Questions 4 and 5, students in the VP sequence were more likely to provide responses that aligned with the ideal, accepted physical relationships. For example, students in the VP sequence were more likely to respond that the work required to lift an object a certain height stayed the same or was similar for various pulley systems than were students in the PV sequence. Similarly, students in the VP sequence were more likely to respond that the required work to lift an object was the same or similar to the change in the object's potential energy than were students in the PV sequence. Students in the

VP sequence were more likely to provide these answers after both the virtual and physical experiments. In Question 5, students in the PV sequence were more likely to state that the work changed and the potential energy did not. This response did not adequately address the question, which asked students to compare work and potential energy. Rather these students provided a response that discussed work and potential energy separately. Similarly, in Question 9, students in the PV sequence were more likely to provide a response that described the nature of the relationship between mechanical advantage and supporting strands rather than an answer that made a comparison between the physical and virtual experiment, as was asked. These results seem to indicate that the VP sequence helped students to provide more productive responses than the PV sequence. Possible learning theories of learning with which these results align are discussed in Section 5.4.

## 5.2 Pulley Study #2: PWF09

The PWF09 study design was very similar to that of the PWS09 study. Students performed experiments with both physical and virtual manipulatives, in either the physical-virtual (PV, N=67) sequence or virtual-physical (VP, N=58) sequence. For a more complete description of the study, see Section 4.2.2.

After performing experiments with each manipulative, students answered a set of analysis questions. In this section I describe the questions and the categories of responses that emerged from the analysis. In addition, I present the results of the chi-square test for independence for two comparisons: responses provided after the first experiment in each sequence (which addresses whether students responded differently after performing only the physical or only the virtual experiment) and responses provided after the physical experiment in each sequence (which addresses whether the virtual activity influences how students interpret the data from the physical experiment). Fisher's exact test was used when expected cell counts were less than five. A significant result indicates that the responses from the PV and VP sequences represent two different populations. Because two comparisons were performed with the same data, the significance level (α) was reduced from 0.050 to 0.025 (Everitt, 1992). When a significant result was found, adjusted residuals were examined to determine which cells contributed to the significance. Adjusted residuals greater than 1.96 were taken to indicate significant cells (Haberman, 1973).

### *5.2.1 WQ1: Applied Force*

WQ1 asked, “Based on your data, which pulley setup required the **smallest effort (force)** to lift the load?” The physically correct response is that the double compound pulley required the least force of the pulley systems tested as it had the most supporting strands. As shown in Figure 5.10 below, the majority (about 90%) of students correctly identified the double compound system as the pulley setup that required the least force. However, a few students identified alternate pulley systems. After performing the physical experiment, a small percentage (6%) of students in the PV sequence identified the single compound pulley as requiring the least force to lift the load. After performing the virtual experiment, a very small percentage (2%) of students in the VP condition identified the single movable pulley as requiring the least force to lift the load.

The chi-square test for independence was performed with the categories “double compound” and “other pulley”. In the comparison between responses provided after the first experiment (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(1, N=125)=3.9$, $p=.067$. However, in the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were significantly different, $\chi^2(1, N=125)=6.3$, $p=.015$. It is not clear why the virtual experience improved the likelihood that students would identify the correct pulley system in the physical experiment.

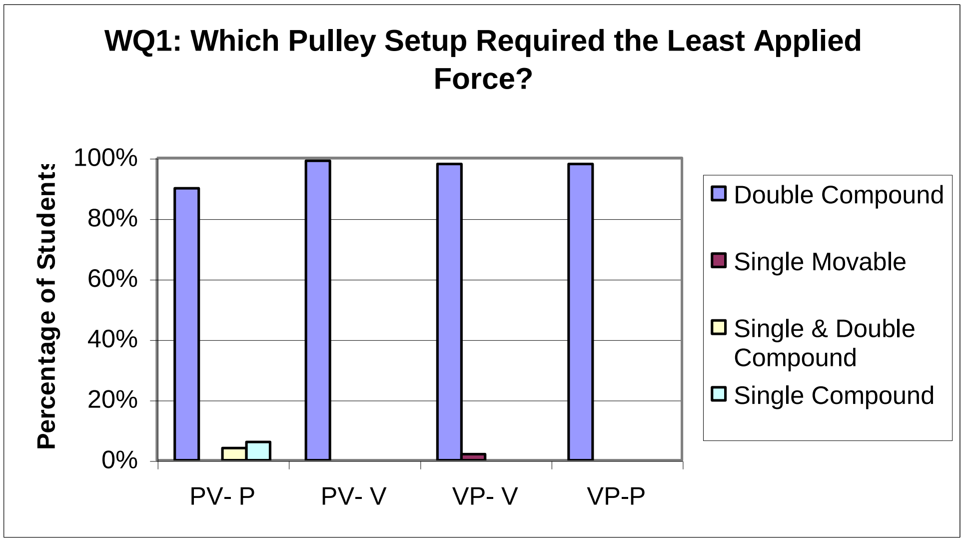


**Figure 5.10 PWF09 Worksheet Question 1 responses.**

### *5.2.2 WQ2: Applied Force and Distance Pulled*

WQ2 asked, “Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?” The physically correct response is that the applied force needed decreases as the distance pulled increases. As shown in Figure 5.11 below, the vast majority of students (about 90%) responded that the required force decreased as the distance pulled increased in each experiment. A small percentage of students gave different answers. After performing the physical experiment, a few students in the PV sequence responded that the force did not change (6%) or increased (3%) as the distance pulled increased. Even fewer students provided these responses after performing the virtual experiment. After performing the virtual experiment, a few students in the VP sequence responded that the force did not change (5%) or increased (2%) as the distance pulled increased in the virtual experiment. In the VP sequence, these responses did not occur after students performed the physical experiment.

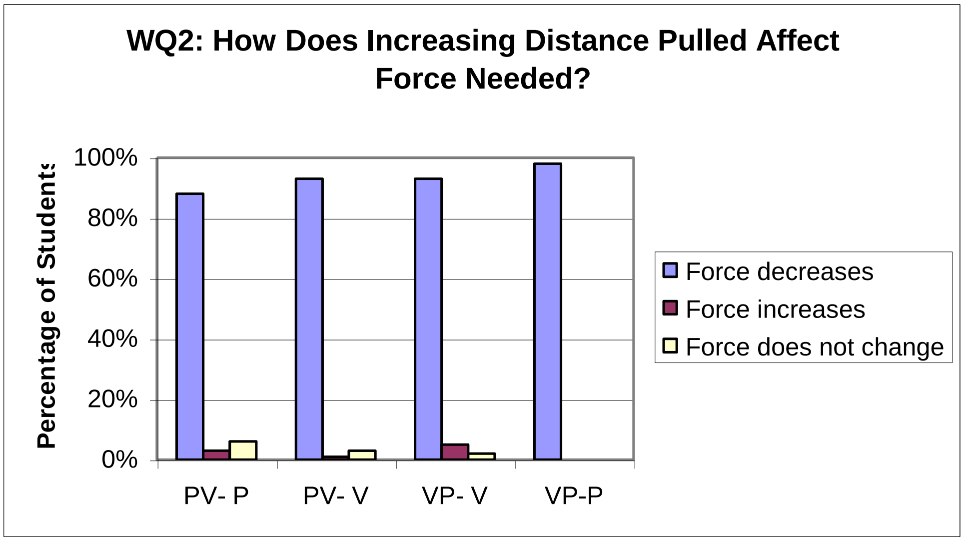


**Figure 5.11 PWF09 Worksheet Question 2 responses.**

The chi-square test for independence was performed with the categories “force decreased”, “force increased”, “force didn’t change” and “other.” For the comparison between responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(3, N=125)=3.1$, p=.358. Similarly, in the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were not significantly different, $\chi^2(3, N=124)=6.2, p=.039$. It is perhaps surprising that students in the two sequences were equally successful in describing the relationship between force and distance pulled. One may have expected the physical manipulative to better support students' understanding of force and distance since force and distance are physically experienced in the physical experiment. However, it appears the simulation is equally as effective as the physical equipment in supporting students' understanding of this relationship.

### *5.2.3 WQ3: Distance Pulled and Distance Moved*

WQ3 asked, "Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?" The physically correct response is that the distance pulled is four times greater than the distance the object moved for the double compound pulley system. As shown in Figure 5.12 below, the majority of students responded either in general that the distance pulled was greater than the distance the object moved (about 60% or more) or more specifically that the distance pulled was four times the distance the object moved (percentage varied by sequence). After performing the physical experiment, a few students in the PV sequence (9%) responded that the distance pulled was three times the distance the object moved. Across the activities, a very small percentage of students responded that the distance pulled and the distance the object moved were about the same (about 3%) or that the distance pulled was less than the distance the object moved (4% or less).

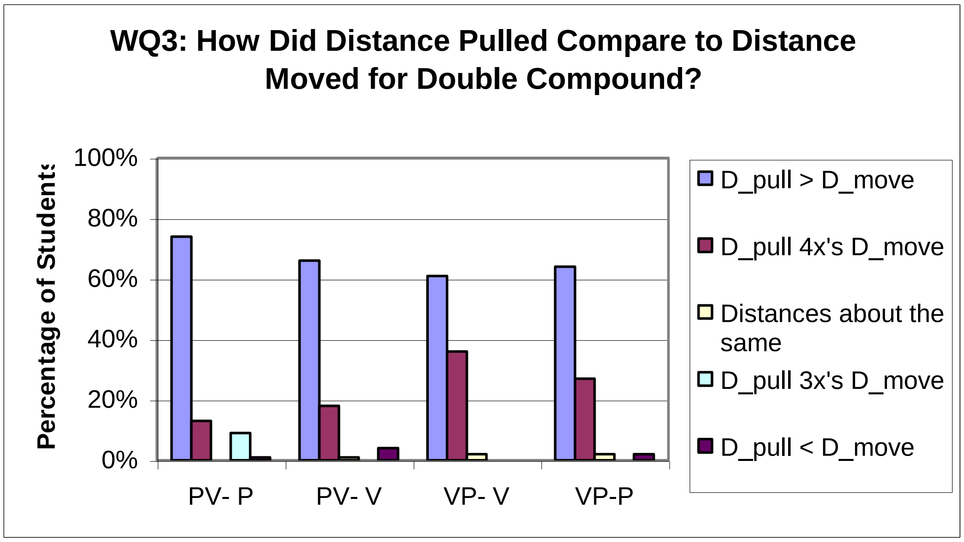


**Figure 5.12 PWF09 Worksheet Question 3 responses.**

The chi-square test for independence was performed with the categories “distance pulled is greater than distance moved”, “distance pulled is four times greater than distance moved”, “distance pulled and distance moved are about the same”, “distance pulled is three times distance moved”, “distance pulled is less than distance moved” and “other.” For the comparison between responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were significantly different, $\chi^2(5, N=125)=14.9, p=.002$. Students were more likely to respond that the distance pulled was four times the distance moved after performing the virtual experiment, but to respond that the distance pulled was three times the distance moved in the physical experiment. This difference is not surprising because the virtual activity provided more exact data whereas data from the physical experiment was subject to frictional effects and measurement errors. In the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were not significantly different, $\chi^2(5, N=124)=10.5, p=.032$. As with WQ2, it is perhaps surprising that the physical and virtual manipulatives provided equal support for students’ understanding of distance since the physical experiment allowed students to physically experience the distances pulled and moved. However, it appears the support provided by the simulation was equally as effective as the kinesthetic experience.

### *5.2.4 WQ4: Work*

WQ4 asked, "Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?" In the simulation, the work need to lift the object is constant across all pulley setups. In the physical experiment, however, students observe fluctuations in the work needed due to frictional effects and measurement errors.

Students' answers to this question varied based on the manipulative they used and the sequence in which they used the manipulatives, as shown in Figure 5.13 below. In both sequences, when students performed the experiment with the computer simulation, the majority of students (more than 75%) responded that work was constant as the pulley system changed. When using the computer simulation, a larger percentage of students in the PV sequence (19%) than in the VP sequence (2%) responded that the work got easier as the pulley system got more complex. In the PV sequence, when students used the physical equipment, the majority of students responded that the work got easier (64%) or changed (18%) as the pulley system got more complex. A very small percentage of students responded that the work was constant (4%) or nearly constant (3%) when the pulley system changed. However, when students in VP sequence used the physical manipulatives, the majority of students responded that the work was constant (41%) or nearly constant (22%) when the pulley system changed. A smaller percentage of students than in the PV sequence responded that the work got easier (5%) or changed (14%) as the pulley system got more complex. In addition, a very small percentage of students (5%) responded that the work increased as the pulley system got more complex.

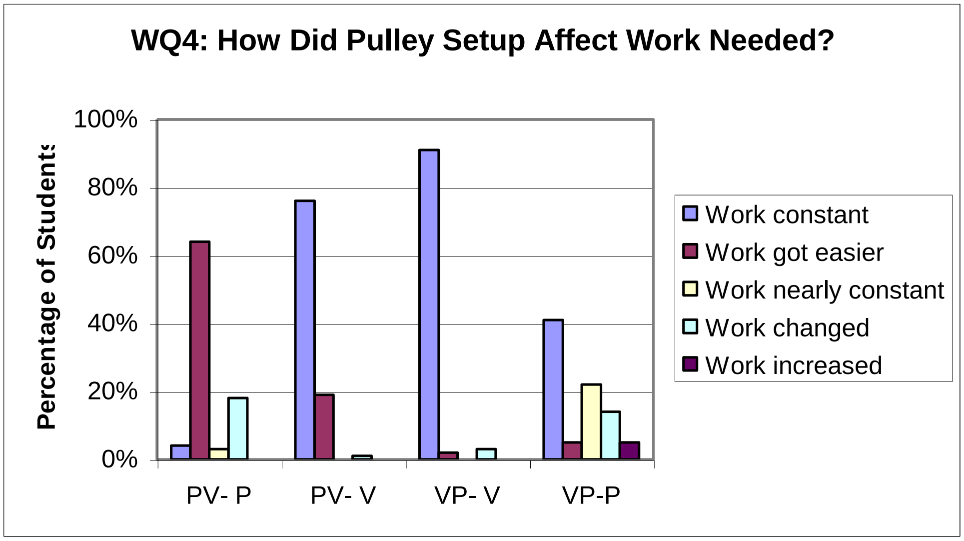


**Figure 5.13 PWF09 Worksheet Question 4 responses.**

The chi-square test for independence was performed with the categories "work was constant", "work got easier", "work was nearly constant", "work changed", "work increased" (for second comparison only) and "other." For the comparison between responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were significantly different, $\chi^2(4, N=125)=112.8, p<.001$. After performing only the virtual experiment, students were more likely to respond that the work stayed the same when the pulley system was changed. After performing only the physical experiment, however, students were more likely to respond that work got easier when the pulley system got more complex or that the work changed when the pulley system changed. This result is not surprising as the simulation provided work data based on idealized conditions; thus, the values for work for lifting the same object to the same height were exactly equal. On the other hand, the work values varied slightly between pulley systems in the physical experiment, which is reflected in students' responses.

For the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again significantly different, $\chi^2(5, N=121)=69.9, p=<.001$. Students in the PV sequence were more likely to respond that work got easier as the pulley systems got more complex, while students in the VP sequence were more likely to respond that work stayed constant or nearly constant (provided by majority of VP students) or increased across pulley systems (provided by a few VP students). This result may indicate that the VP sequence helped students to focus on the similarity of the work values in the physical experiment rather than the fluctuations.

### *5.2.5 WQ5: Work and Potential Energy*

WQ5 asked, "Based on your data, how does **work** compare to **potential energy** for a given pulley system?" In the simulation, the work needed to lift the load was equal to the change in the load's potential energy. In the physical experiment, however, the work needed and change in potential energy were not exactly equal due to frictional effects and measurement errors.

As shown in Figure 5.14 below, students' responses to this question were dependent on the manipulative and sequence in which the manipulatives were used. After using the computer simulation in the VP sequence, the majority of students (52%) responded that the work and potential energy were the same. After performing the experiment with physical equipment, the most common responses in the VP sequence were that the work and potential energy were equal (14%) or very similar (28%). A few students (14%) responded that the work changed while the potential energy did not. A small percentage of students provided alternate answers, such as that the work was greater (7%) or less than the potential energy (5%) or that the work and potential energy were both constant (3%). Students in the PV sequence provided a variety of answers after using both the physical equipment and the computer simulation. After using the physical manipulatives, the majority of students either responded that the work changed while the potential energy did not (26%) or that the work and potential energy were not related (22%). However, students were spread across all of the response categories, with very few students responding that the work and potential energy were the same (6%) or very similar (1%). After performing the experiment with the computer simulation, students in the PV sequence mainly responded that the work and potential energy were equal (28%) or that both the work and the potential energy were constant (24%). More students in the PV sequence than in VP sequence provided alternate answers, such as that the work and potential energy were not related, after using the virtual manipulative.

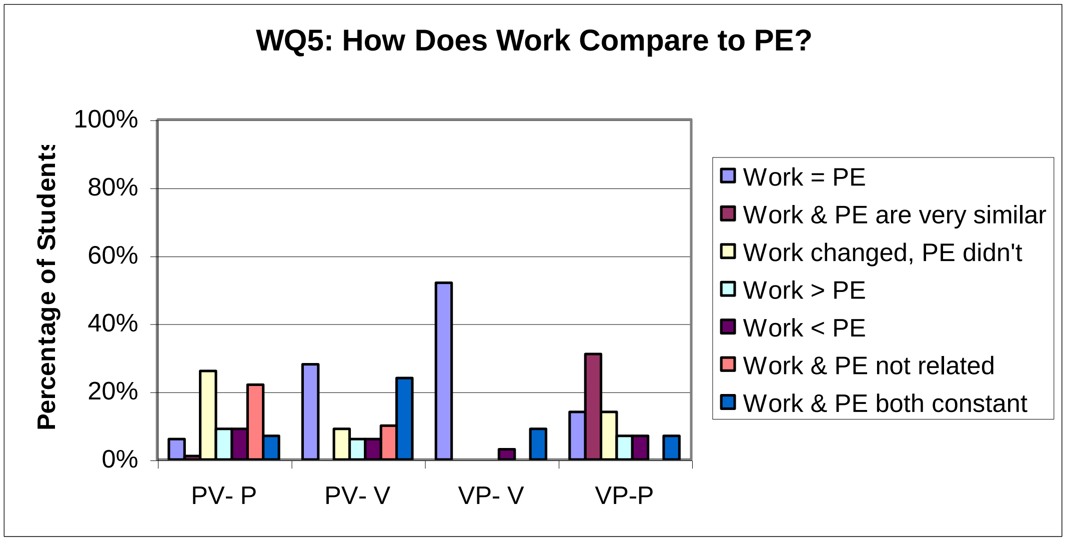


**Figure 5.14 PWF09 Worksheet Question 5 responses.**

The chi-square test for independence was performed with the categories “work equaled potential energy,” “work and potential energy were similar,” “work changed and potential energy stayed the same,” “work was greater than potential energy,” “work was less than potential energy," "work and potential energy are not related," "work and potential energy were both constant" and "other." For the comparison between responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were significantly different, $\chi^2(7, N=125)=68.9, p=<.001$. After performing only the virtual experiment, students were more likely to respond that work and potential energy were equal. After performing only the physical experiment, students were more likely to respond that work changed but potential energy did not, work was greater than potential energy, or work and potential energy were not related. In the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again significantly different, $\chi^2(7, N=120)=40.5, p=<.001$. Students from the VP sequence were more likely to respond that work and potential energy were similar, while students from the PV sequence were more likely to respond that work and potential energy were not related. To a certain extent, these results are not surprising because the responses reflect the trends students saw in the data from the virtual (work exactly equal to potential energy) and physical (work slightly greater than potential energy) experiments. However, it also appears that students in the VP sequence were more likely to make comparisons between work and potential energy, while students in the PV sequence were more likely to talk about the two concepts separately or to explicitly state that work and potential energy were not related. This result may indicate that the representations, such as bar charts, used to present data in the simulation provided better support for making comparisons between these concepts than the physical experiment did.

### *5.2.6 WQ6: Mechanical Advantage*

WQ6 asked, "Which pulley setup gave you the *greatest* **mechanical advantage**?" The physically correct response is the double compound pulley system. As shown in Figure 5.15 below, the vast majority (about 90%) of students in both sequences correctly identified the double compound pulley as the pulley setup with the most mechanical advantage. More students in the PV sequence than the VP sequence identified alternate pulley setups as having the most mechanical advantage.

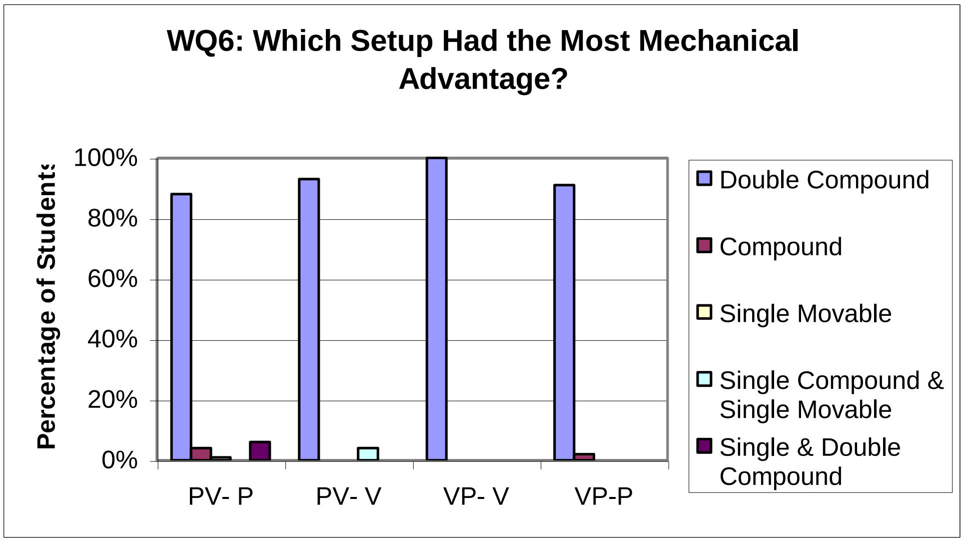


Figure 5.15 PWF09 Worksheet Question 6 responses.

The chi-square test for independence was performed with the categories "double compound pulley" and "other pulley." For the comparison between responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were significantly different, $\chi^2(1, N=125)=7.4$, $p=.007$. This indicates that students had more difficulty identifying the correct pulley system after performing only the physical experiment than after performing only the virtual experiment. It is not clear why the virtual experiment was more likely to help students identify the pulley system with the most mechanical advantage. In the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were not significantly different, $\chi^2(1, N=121)=4.4$, $p=.042$. This is not surprising because the difference in mechanical advantage between the pulley systems was large and easily observable in both the physical and virtual experiments.

### *5.2.7 WQ7: Mechanical Advantage and Supporting Strands*

WQ7 asked, "Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?" The physically correct response is that the mechanical advantage increases when the number of supporting strands is increased. As shown in Figure 5.16 below, the vast majority (about 90%) of students in both sequences correctly responded that the mechanical advantage increased as the number of supporting strands increased. Very few students provided alternate responses.

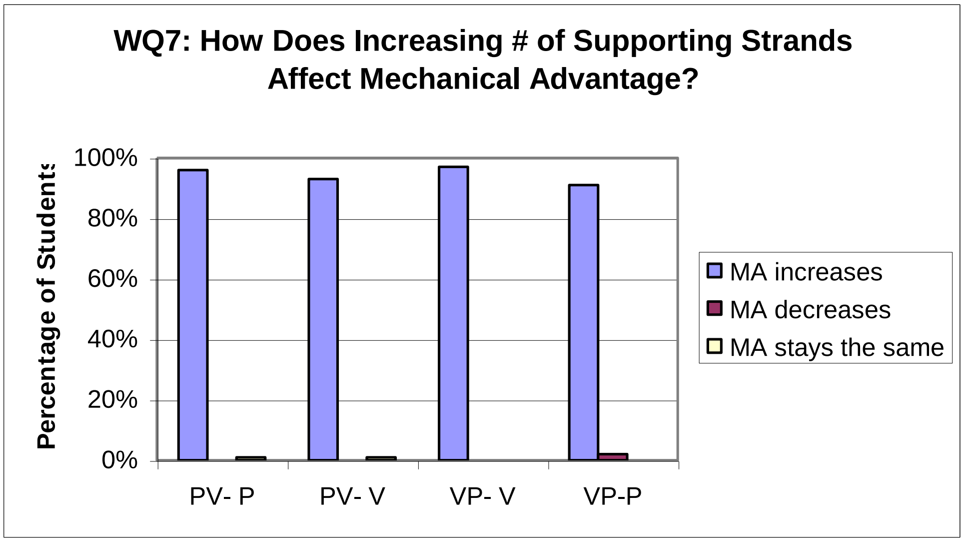


Figure 5.16 PWF09 Worksheet Question 7 responses.

The chi-square test for independence was performed with the categories “mechanical advantage increases”, “mechanical advantage decreases”, “mechanical advantage stays the same” and “other.” For the comparison between responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(3, N=123)=2.1, p=.500$. Similarly, in the comparison between responses provided after the physical experiment (first experiment in PV sequence and second experiment in VP sequence), the two sequences were not significantly different, $\chi^2(3, N=121)=3.2, p=.411$. This result is perhaps surprising since students have the kinesthetic experience of actually stringing the pulleys and creating the supporting strands in the physical experiment and do not have a similar experience in the virtual experiment. However, these results seem to indicate that the physical and virtual manipulatives equally supported students’ understanding of the relationship between supporting strands and mechanical advantage.

### *5.2.8 WQ8: Comparison of Physical and Virtual Experiments (Work and Potential Energy)*

WQ8 asked, “How does the relationship between **work** and **potential energy** in the *experiment* compare with the *simulation*?” While work and potential energy were equal in the virtual experiment due to the simulation’s ideal conditions, they are slightly different in the physical experiment due to frictional effects and measurement errors.

As shown in Figure 5.17 below, students’ responses from both sequences fell in the same major categories. In the PV sequence, a nearly equal number of students responded that the relationship between work and potential energy was the same in the two experiments (34%) and that the work and potential energy were equal in the simulation, but different in the physical experiment (31%). These two responses were also common among students in the VP sequence, although more students responded that the work and potential energy were equal in the simulation and different in the physical experiment (28%) than that the relationship was the same (19%.) More students in the VP sequence (12%) than the PV sequence (3%) responded that the relationship between work and potential energy was about the same in the two experiments. A few students in both sequences responded that the relationship was different (about 10%) or that the work was less accurate in the physical experiment than the simulation (about 5%).

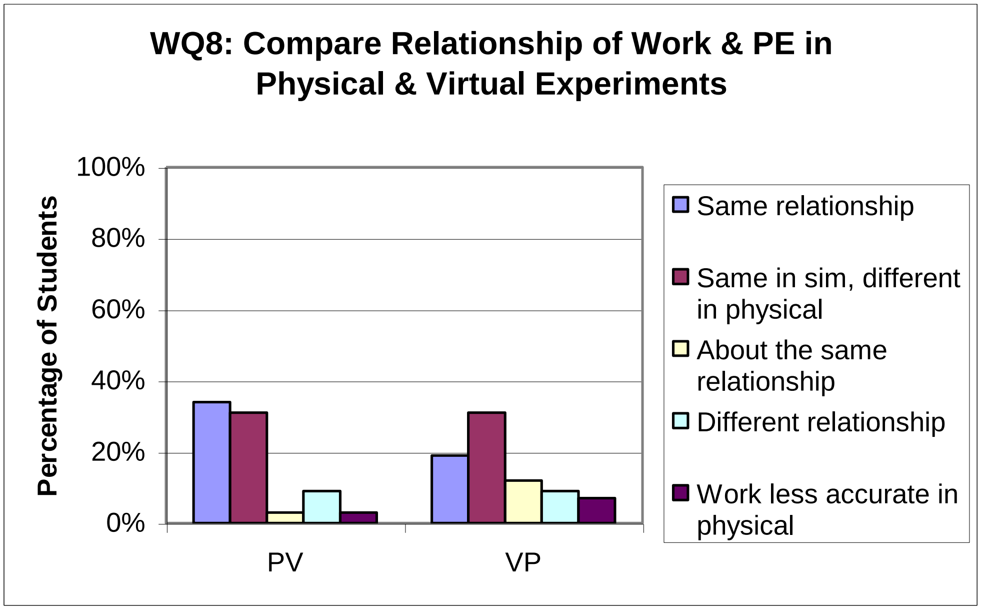


**Figure 5.17 PWF09 Worksheet Question 8 responses.**

The chi-square test for independence was performed with the categories “same relationship in physical experiment and simulation”, “work and potential energy were the same in the simulation but different in the physical experiment”, “about the same relationship in the physical experiment and simulation”, “different relationship in the physical experiment and simulation”, “work less accurate in physical experiment than simulation” and “other.” There was no statistically significant difference between the responses provided by students in the PV and VP sequences, $\chi^2(5, N=120)=7.2, p=.203$. This result is somewhat surprising since it appeared that the VP sequence helped students understand the relationship between work and potential energy better than the PV sequence did.

### *5.2.9 WQ9: Comparison of Physical and Virtual Experiments (Mechanical Advantage and Supporting Strands)*

WQ9 asked, “How does the relationship between **mechanical advantage** and the **number of supporting strands** in the *experiment* compare with the *simulation*?” In the simulation, the mechanical advantage is equal to the number supporting strands. In the physical experiment, the mechanical advantage is close to (but likely not exactly equal to) the number of supporting strands.

As shown in Figure 5.18 below, students’ responses from both sequences follow the same general trend. The majority of students responded that the relationship between mechanical advantage and number of supporting strands was the same (about 50%) or similar (about 20%) between the physical and virtual experiments. Some students in both sequences described the relationship. The majority of these students (about 20%) stated that more supporting strands indicated more mechanical advantage, while a few students (less than 5%) stated that more supporting strands indicated less mechanical advantage.

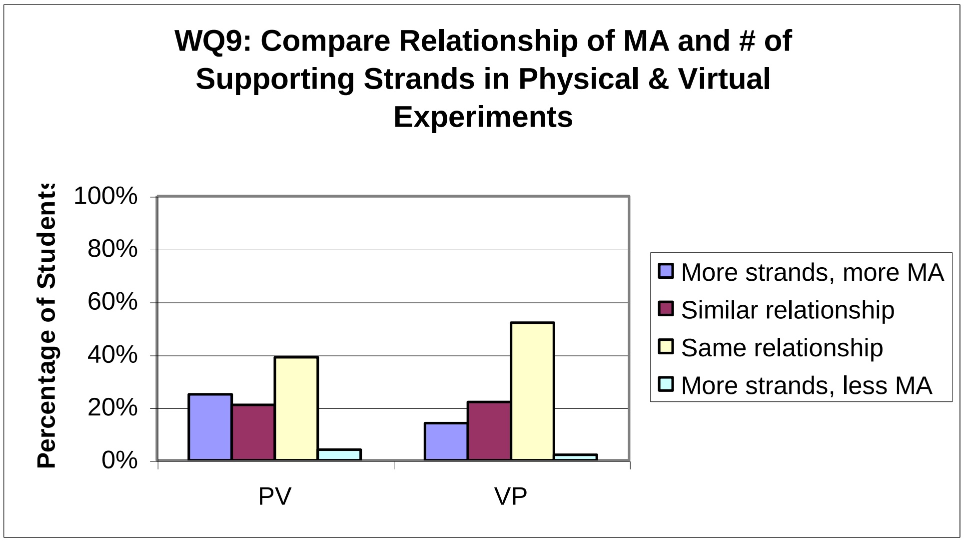


**Figure 5.18 PWF09 Worksheet Question 9 responses.**

The chi-square test for independence was performed with the categories "more supporting strands means more mechanical advantage", "similar relationship in the physical experiment and simulation", "same relationship in the physical experiment and simulation", "more strands means less mechanical advantage" and "other." There was no statistically significant difference between the responses provided by students in the PV and VP sequences, $\chi^2$(4, N=120)=5.2, p=.267. This result is somewhat surprising because it differs from the result of the PWS09 pulley study, where students in the PV sequence were more likely to describe the relationship between number of supporting strands and mechanical advantage than were students in the VP sequence. While the PWS09 finding supported the idea that having the virtual experience first appears to help students make comparisons between concepts, the PWF09 finding does not. Instead, this result appears to indicate that the physical and virtual manipulatives equally supported students' abilities to make comparisons between the physical and virtual experiments.

### *5.2.10 Summary*

In the previous sections, I have presented students' responses to the pulley analysis questions and the results of the chi-square test for independence on the responses provided in the PV and VP sequences for two specific contrasts. The first contrast was between the responses provided after the first experiment in each sequence (physical experiment in PV and virtual experiment in VP). This contrast addresses whether students responded to each question differently after using the physical or virtual manipulative. The second contrast was between the responses provided after the physical experiment in each sequence (first experiment in PV sequence and second experiment in VP sequence). This contrast addresses whether performing the virtual experiment before the physical experiment affects the way students interpret the data from the physical experiment. I chose this contrast because I believe it is of interest to physics instructors, who tend to place value on developing their students' ability to perform and analyze real-world experiments. Table 5.2 below summarizes the results of these contrasts. As discussed above, since two contrasts were performed the significance level was reduced from $\alpha=0.050$ to $\alpha=0.025$ (Everitt, 1992). Fisher's exact test was used for contrasts where expected counts in any category were less than 5 (which was all of the contrasts in this study).

### Table 5.2 Summary of PWF09 Worksheet Question Statistics

| | | **First Experiment** (PV physical responses compared to VP virtual responses) | | | **Physical Experiment** (PV physical responses compared to VP physical responses) | | |
|---|---|---|---|---|---|---|---|
| **Q#** | **Question Description** | $\chi^{2+}$ | **p**$^{++}$ | **V**$^{+++}$ | $\chi^{2+}$ | **p**$^{++}$ | **V**$^{+++}$ |
| 1 | Applied Force | $\chi^2$(1, N=125) =3.9 | .067 | .18 | $\chi^2$(1, N=124) =6.3 | **.015** | .23 |
| 2 | Applied Force and Distance Pulled | $\chi^2$(3, N=125) =3.1 | .358 | .16 | $\chi^2$(3, N=124) =6.2 | .039 | .22 |
| 3 | Distance Pulled and Distance Moved | $\chi^2$(5, N=125) =14.9 | **.002** | .35 | $\chi^2$(5, N=124) =10.5 | .032 | .29 |
| 4 | Work | $\chi^2$(4, N=125) =112.8 | **<.001** | .95 | $\chi^2$(5, N=121) =69.9 | **<.001** | .76 |
| 5 | Work and Potential Energy | $\chi^2$(7, N=125) =68.9 | **<.001** | .74 | $\chi^2$(7, N=120) =40.5 | **<.001** | .58 |
| 6 | Mechanical Advantage | $\chi^2$(1, N=125) =7.4 | **.007** | .24 | $\chi^2$(1, N=121) =4.4 | .042 | .19 |
| 7 | Mechanical Advantage and Supporting Strands | $\chi^2$(2, N=123) =2.1 | .500 | .13 | $\chi^2$(3, N=121) =3.2 | .411 | .16 |
| | | (Only asked after final experiment in each sequence) | | | | | |
| 8 | Comparison of Physical and Virtual Experiments: Work and Potential Energy | $\chi^2$(5, N=120) =7.2 | .203 | .24 | | | |
| 9 | Comparison of Physical and Virtual Experiments: Mechanical Advantage and Supporting Strands | $\chi^2$(4, N=120) =5.2 | .267 | .21 | | | |

$^{+}$The format is $\chi^2$(degrees of freedom, N) =chi-square statistics

$^{++}$Significance value

$^{+++}$Effect size

The chi-square test for independence indicated that the PV and VP sequences only represented two different populations for Questions 1 (physical experiment contrast), 3 (first experiment contrast), 4 (both contrasts), 5 (both contrasts) and 6 (first experiment contrast). The results for Questions 4 and 5 are similar to those found in the PWS09 pulley study. Students in the VP sequence were more likely to provide responses that align with the ideal relationships about work and potential energy. Several theories of learning with which these results align are discussed in Section 5.4.

The effect sizes (V in Table 5.2) for Questions 1, 3 and 6 are smaller than for Questions 4 and 5, which indicates a weaker relationship between the manipulative sequence and students' responses. In Question 1, for the physical experiment contrast, students in the VP sequence were more likely than students in the PV sequence to correctly identify they pulley system that required the least force to lift the load. It is unclear why the VP sequence led to better performance on this question. Similarly, in Question 6, for the first experiment contrast, students in the VP sequence were more likely to correctly identify the double compound pulley as the system that had the most mechanical advantage. Again, it is unclear why the virtual experiment led to better performance on this question. In Question 3, for the first experiment contrast, students in the PV sequence were more likely to respond that the distance pulled was three times the distance moved for the double compound pulley, while students in the VP sequence were more likely to respond that the distance pulled was four times the distance moved. This result is not surprising as the responses are very similar and likely reflect the differences in the idealized data in the simulation and measurement error sin the physical experiment.

## 5.3 Pulley Study #3: CoPF09

As in the previous studies, students in the CoPF09 used both physical and virtual manipulatives to perform experiments about pulleys. In the CoPF09 study, students choose whether to complete the physical or the virtual experiment first. Students did not answer the physical experiment and simulation comparison questions (WQ8 and WQ9 from previous studies). For a more complete description of the study, see Section 4.2.3. As in the previous sections, I first discuss students' responses to the analysis questions, followed by statistical analysis of the responses using the chi-square test for independence, and finally summarize of the findings of the worksheet analysis.

### *5.3.1 WQ1: Applied Force*

WQ1 asked, "Based on your data, which pulley setup required the **smallest effort (force)** to lift the load?" The physically correct response is that the double compound pulley system requires the least applied force. As shown in Figure 5.19 below, nearly all students correctly identified the double compound system as the pulley setup that required the least applied force. However, a few students identified alternate pulley systems. After performing the physical experiment in the VP sequence, a very small percentage (3%) of students identified the single compound system as requiring the least force to lift the load.

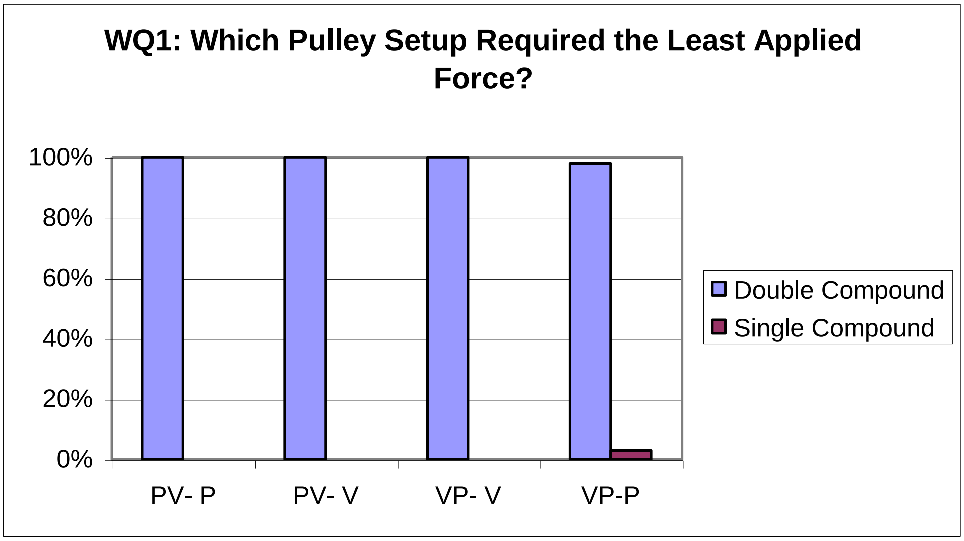


**Figure 5.19 CoPF09 Worksheet Question 1 responses.**

For the responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the chi-square test for independence was not performed since all students provided the same response. For the responses provided after the physical experiment in both sequences (first experiment in PV sequence and second experiment in VP sequence), the two sequences were not significantly different, $\chi^2(1, N=99)=1.5, p=.404$. This result is not surprising since the difference in force between the double compound pulley and the other pulley systems tested was large and should have been clear in both the physical and virtual experiments.

### *5.3.2 WQ2: Distance Pulled and Distance Moved*

WQ2 asked, "Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?" The physically correct response is that the necessary applied force decreases when the distance pulled increases. As shown in Figure 5.20 below, the majority of students (about 80%) responded that the required force decreased as the distance pulled increased after each experiment. A small percentage of students gave different answers. A few students (about 10%) responded that the force increased when the distance pulled increased for both activities in both sequences. After the first experiment in both sequences, a few students (about 5%) responded that the force did not change. In addition, after performing the physical experiment, a very small percentage (5%) of students in the PV sequence responded that the relationship between distance pulled and force depended on the type of pulley.

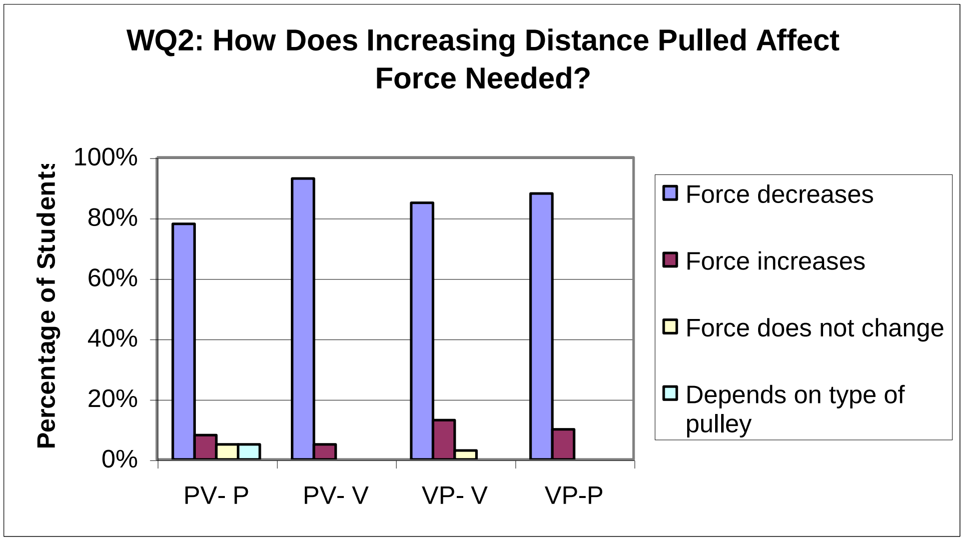


**Figure 5.20 CoPF09 Worksheet Question 2 responses.**

The chi-square test for independence was performed with the categories “force decrease”, “force increased”, “force didn’t change”, “force depended on type of pulley” and “other.” For the responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(4, N=99)=3.5$, p=.487. Similarly, for the responses provided after the physical experiment in each sequence (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again not significantly different, $\chi^2(4, N=99)=3.8$, p=.429. It may be surprising that students in the PV and VP sequences were equally successful on this question since the physical experiment provided students with the kinesthetic experience of feeling the force and pulling the rope a longer distance. However, it appears that the simulation was equally effective as the physical experiment in helping students to understand the relationship between force and distance in the context of pulleys.

### *5.3.3 WQ3: Distance Pulled and Distance Moved*

WQ3 asked, "Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?" For the double compound pulley, which was the pulley system with the least applied force needed, the distance pulled is four times the distance moved. As shown in Figure 5.21 below, the majority of students responded either in general that the distance pulled was greater than the distance the object moved (about 50%) or more specifically that the distance pulled was four times the distance the object moved (about 20%). After the physical experiment in both sequences, a small percentage of students (about 10%) responded that the distance pulled was three times the distance the object moved. Across the experiments, a small number of students responded that the distance pulled and the distance the object moved were about the same (about 5%) or that the distance pulled was less than the distance the object moved (less than 5%).

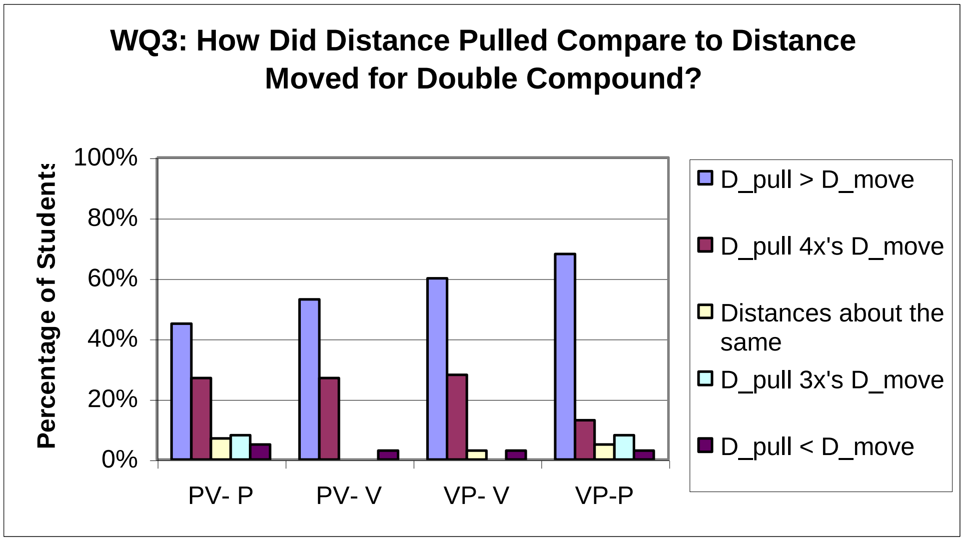


**Figure 5.21 CoPF09 Worksheet Question 3 responses.**

The chi-square test for independence was performed with the categories "distance pulled greater than distance moved", "distance pulled four times distance moved", "distances pulled and moved about the same", "distance pulled three times distance moved", "distance pulled less than distance moved" and "other." In the comparison between the responses provided after the first experiment in each sequence (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(5, N=99)=5.3, p=.373$. Similarly, for the responses provided after the physical experiment in each sequence (first experiment in PV sequence and second experiment in VP sequence), the two sequences were not significantly different, $\chi^2(5, N=99)=4.9, p=.436$. As with WQ2, it is perhaps surprising that the physical and virtual manipulatives provided equal support for students' understanding of distance since the physical experiment allowed students to physically experience the distances pulled and moved. However, it appears the support provided by the simulation was equally as effective as the kinesthetic experience.

### *5.3.4 WQ4: Work*

WQ4 asked, "Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?" In the virtual experiment, the work needed to lift the load should have been the same across all pulley systems. However, the work for the double compound pulley was 0.1 J more than the work for the other pulley systems in this implementation. In the physical experiment, the work varied slightly between the pulley systems due to frictional effects and measurement errors.

Students' responses to this question varied based on the manipulative they used and the sequence in which they used the manipulatives, as shown in Figure 5.22 below. In both sequences, when students used the computer simulation, they tended to answer that the work was constant (about 25% of students) or nearly constant (about 25% of students) when the pulley system changed. In this implementation, the work was 0.1 J higher for the double compound pulley in the simulation, which is reflected in the relatively high percentage (13% in PV sequence and 30% in VP sequence) of students who answered that the work changed for the double compound pulley system. Some students also answered that the work decreased (about 15%), increased (5% in PV sequence only) or changed (13% in PV sequence only) as the pulley system got more complex. In the PV sequence, when the students performed the physical experiment the majority of students responded that the work got easier (60%) or changed (23%) as the pulley system got more complex. A small percentage of students responded that the work was constant (5%) or nearly constant (2%) or that work increased (2%) as the pulley system got more complex. The same trend is observed in the VP sequence when the students performed the physical experiment. However, a lower percentage of students responded that the work got easier (40%) and a higher percentage of students responded that the work was constant (15%), nearly constant (13%), or increased (8%) as the pulley system got more complex.

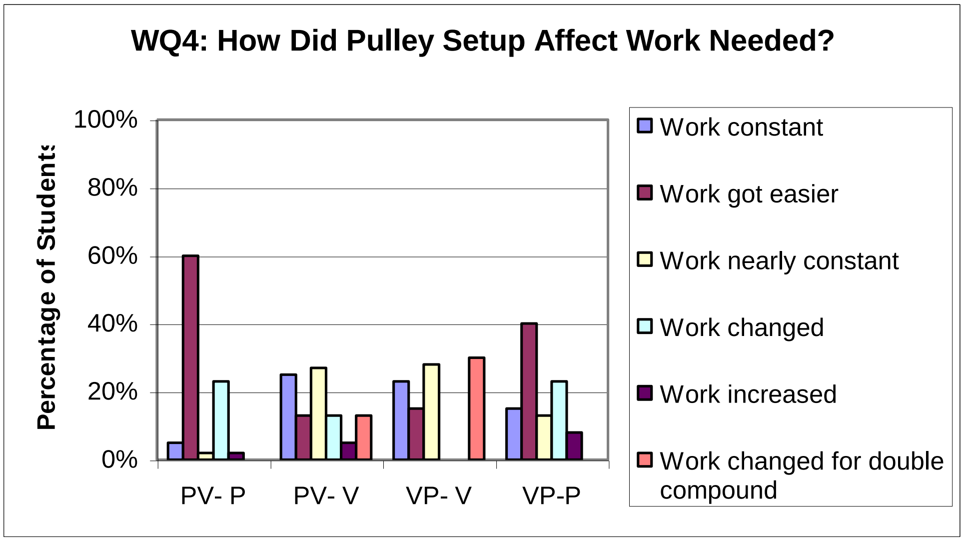


**Figure 5.22 CoPF09 Worksheet Question 4 responses.**

The chi-square test for independence was performed with the categories "work stayed constant", "work got easier", "work stayed nearly the same", "work changed", "work increased", "work changed for the double compound pulley" and "other." In the comparison between responses provided after the first experiment (physical experiment in PV sequence and virtual experiment in the VP sequence), the two sequences were significantly different, $\chi^2$(6, N=99)=51.7, p<.001. After performing only the virtual experiment, students were more likely to respond that work stayed constant, work was nearly constant, or to provide an alternate response ("other"). In the PV sequence, students were more likely to respond that work got easier as the pulley systems got more complex or that work changed when the pulley system changed. Similarly, in the comparison between the responses provided after the physical experiment in both sequences (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again significantly different, $\chi^2$(5, N=99)=11.9, p=.025. In the VP sequence, students were more likely to respond that work was nearly constant, while in the PV sequence students were more likely to respond that work got easier as the pulley systems got more complex.

Overall, students in the VP sequence were more likely to respond that work was constant or nearly constant across pulley systems than were students in the PV sequence. As has been described in previous sections, in the VP sequence students are first presented with data from idealized conditions, which nearly identical work values for each pulley system.

### *5.3.5 WQ5: Work and Potential Energy*

WQ5 asked, "Based on your data, how does **work** compare to **potential energy** for a given pulley system?" In the simulation, the work needed to lift the load should have been equal to the change in the load's potential energy. However, the work and potential energy were slightly different for the double compound pulley system in this implementation. In the physical experiment, the work and potential energy were slightly different due to frictional effects and measurement errors.

As shown in Figure 5.23 below, students' responses varied based on the type of manipulative used. There was a similar trend of responses across both sequences when students used the computer simulation. The majority of students responded either that the work and potential were the same (about 30%) or nearly the same (about 25%). Also, due to a glitch in the simulation, many students in both sequences responded that the work and potential energy were the same except for the double compound pulley (about 15%). The responses students provided after performing the physical experiment varied based on the order in which they used the manipulatives. The majority (37%) of students in the PV sequence responded that the work changed, but the potential energy did not. After performing the physical experiment, no students in the PV sequence responded that the work and potential energy were equal, and very few students (2%) responded that the work and potential energy were very similar. In the VP sequence, after performing the physical experiment, the majority of students responded either that the work changed and the potential energy did not (26%) or that the work was greater than the potential energy (28%). However, more students than in the PV sequence responded that the work and potential energy were equal (8%) or very similar (20%).

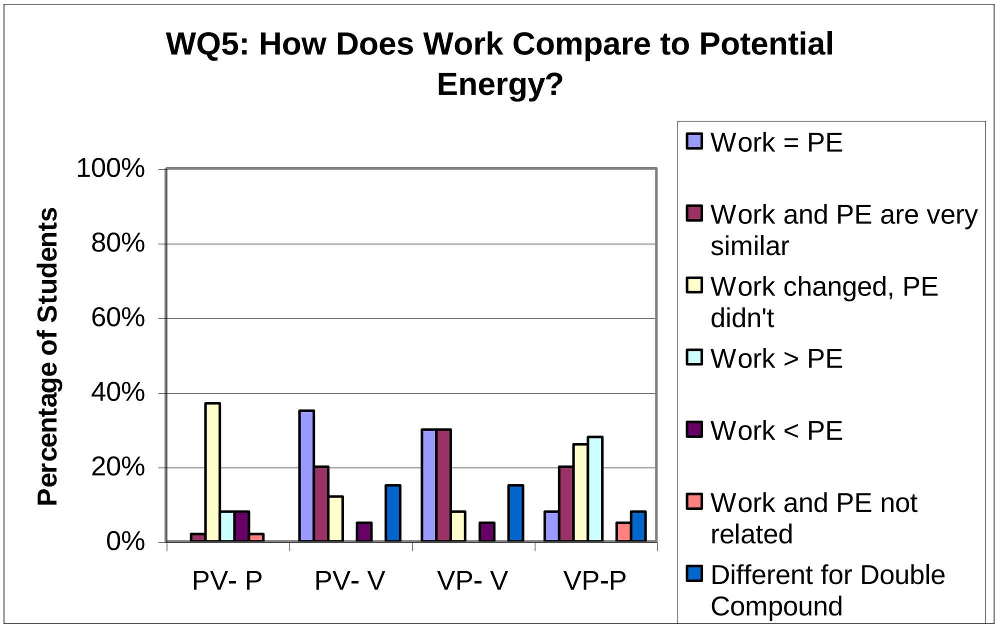


**Figure 5.23 CoPF09 Worksheet Question 5 responses.**

The chi-square test for independence was performed with the categories “work was equal to potential energy”, “work and potential energy were similar”, “work changed and potential energy did not”, “work was greater than potential energy”, “work was less than potential energy”, “work and potential energy are not related”, “work was different for the double compound pulley” and “other”. In the comparison between responses provided after the first experiment (physical experiment in the PV sequence and virtual experiment in the VP sequence), the two sequences were significantly different, $\chi^2(7, N=99)=44.6, p<.001$. After performing only the virtual experiment, students were more likely to respond that the work and potential energy were the same or that the work was different for the double compound pulley. After performing only the physical experiment, students were more likely to respond that work changed and potential energy did not. Similarly, in the comparison between responses provided after the physical experiment in both sequences (first experiment in the PV sequence and second experiment in the VP sequence), the two sequences were again significantly different, $\chi^2(7, N=99)=23.6, p<.001$. Students in the VP sequence were more likely to respond that work and potential energy were equal, work was greater than potential energy, or work was different for the double compound pulley. Students in the PV sequence were more likely to provide another response.

Students' responses to WQ5 follow a similar trend as WQ4. Students who used the virtual manipulative first tended to focus on the similarity of the work values, which is not surprising as the simulation presents data from idealized conditions. In addition, it appears the simulation helps students to make comparisons between work and potential energy as students who used the physical manipulative first were more likely to respond that work and potential energy were not related. This may be due to the graphical representation used to present the work and potential energy data in the simulation.

### *5.3.6 WQ6: Mechanical Advantage*

WQ6 asked, "Which pulley setup gave you the *greatest* **mechanical advantage**?" The physically correct response is that the double compound pulley system had the most mechanical advantage. As shown in Figure 5.24 below, the vast majority (more than 90%) of students in both sequences correctly identified the double compound pulley as the pulley setup with the most mechanical advantage. Very few students identified alternate pulley systems.

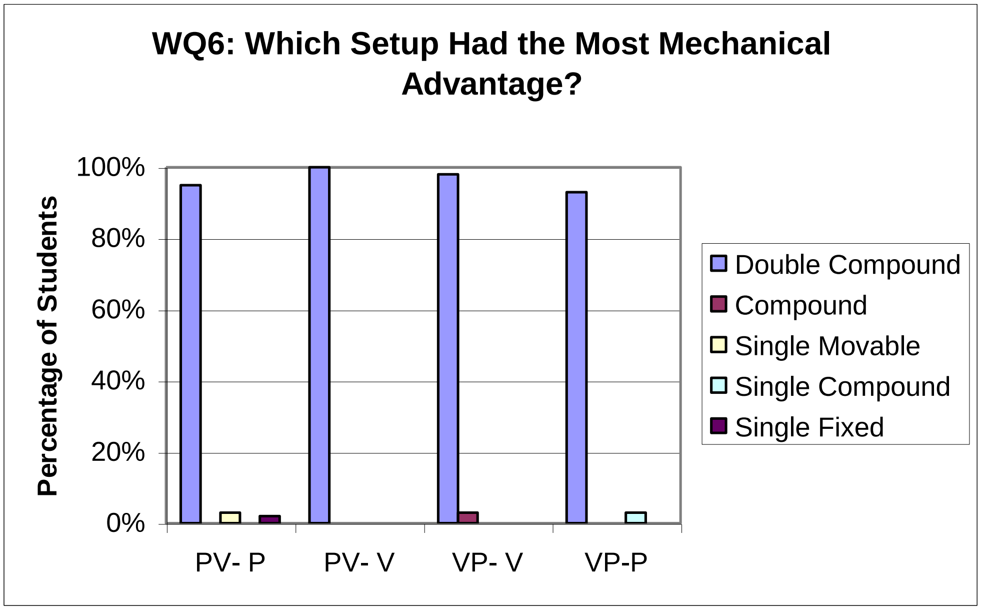


**Figure 5.24 CoPF09 Worksheet Question 6 responses.**

The chi-square test for independence was performed with the categories "double compound pulley" and "other pulley". In the comparison between the responses provided after the first experiment (physical experiment in PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(1, N=99)=0.4$, p=.645. Similarly, in the comparison between responses provided after the physical experiment in each sequence (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again not significantly different, $\chi^2(1, N=99)=0.0$, p=1.00. This is not surprising because the difference in mechanical advantage between the pulley systems was large and easily observable in both the physical and virtual experiments.

### *5.3.7 WQ7: Mechanical Advantage and Supporting Strands*

WQ7 asked, "Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?" As shown in Figure 5.25 below, the vast majority (about 90%) of students responded that the mechanical advantage increased as the number of supporting strands increased. In the PV sequence, a few students (about 10%) responded that the object was easier to move when there were more supporting strands instead of responding directly about the mechanical advantage. In the VP sequence, a few students (3%) provided the "easier to move" response, but only after performing the physical experiment.

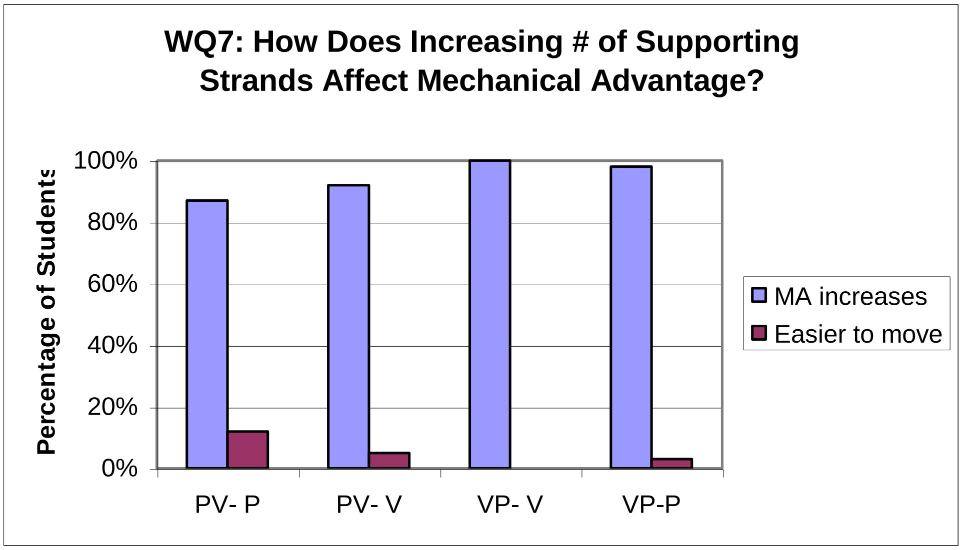


**Figure 5.25 CoPF09 Worksheet Question 7 responses.**

The chi-square test for independence was performed with the categories "mechanical advantage increases", "mechanical advantage decreases" and "other". For the comparison between responses provided after the first experiment in each sequence (physical experiment in

PV sequence and virtual experiment in VP sequence), the two sequences were not significantly different, $\chi^2(2, N=99)=6.0, p=.039$. Similarly, for the comparison between responses provided after the physical experiment in both sequences (first experiment in PV sequence and second experiment in VP sequence), the two sequences were again not significantly different, $\chi^2(2, N=99)=5.6, p=.050$. This result is perhaps surprising since the physical experiment provided students with the kinesthetic experience of actually stringing the pulleys and creating the supporting strands. The simulation did not mimic this experience. However, the results seem to indicate that the physical and virtual experiments equally supported students' understanding of the relationship between supporting strands and mechanical advantage.

### *5.3.8 Summary*

In the previous sections, I have presented students' responses to the pulley analysis questions and the results of the chi-square test for independence on the responses provided in the PV and VP sequences for two specific contrasts. The first contrast was between the responses provided after the first experiment in each sequence (physical experiment in PV and virtual experiment in VP). This contrast addresses whether students responded to each question differently after using the physical or virtual manipulative. The second contrast was between the responses provided after the physical experiment in each sequence (first experiment in PV sequence and second experiment in VP sequence). This contrast addresses whether performing the virtual experiment before the physical experiment affects the way students interpret the data from the physical experiment. I chose this contrast because I believe it is of interest to physics instructors, who tend to place value on developing their students' ability to perform and analyze real-world experiments. Table 5.3 below summarizes the results of these contrasts. As discussed above, since two contrasts were performed the significance level was reduced from $\alpha=0.050$ to $\alpha=0.025$ (Everitt, 1992). Fisher's exact test was used for contrasts where expected counts in any category were less than 5 (which was all of the contrasts in this study).

**Table 5.3 Summary of CoPF09 Worksheet Contrast Statistics**

| | | **First Experiment** (PV physical responses compared to VP virtual responses) | | | **Physical Experiment** (PV physical responses compared to VP physical responses) | | |
|---|---|---|---|---|---|---|---|
| **Q#** | **Question Description** | $\chi^2$[+] | **p**[++] | **V**[+++] | $\chi^2$[+] | **p**[++] | **V**[+++] |
| 1 | Applied Force | Not performed | -- | -- | $\chi^2(1, N=99)$ =1.5 | .404 | .12 |
| 2 | Applied Force and Distance Pulled | $\chi^2(4, N=99)$ =3.5 | .487 | .19 | $\chi^2(4, N=99)$ =3.8 | .429 | .20 |
| 3 | Distance Pulled and Distance Moved | $\chi^2(5, N=99)$ =5.3 | .373 | .23 | $\chi^2(5, N=99)$ =4.9 | .436 | .22 |
| 4 | Work | $\chi^2(6, N=99)$ =51.9 | **<.001** | .72 | $\chi^2(5, N=99)$ =11.9 | **.025** | .35 |
| 5 | Work and Potential Energy | $\chi^2(7, N=99)$ =44.6 | **<.001** | .67 | $\chi^2(7, N=99)$ =23.6 | **<.001** | .49 |
| 6 | Mechanical Advantage | $\chi^2(1, N=99)$ =0.4 | .645 | .06 | $\chi^2(1, N=98)$ =0.0 | 1.00 | 0 |
| 7 | Mechanical Advantage and Supporting Strands | $\chi^2(2, N=99)$ =6.0 | .039 | .25 | $\chi^2(5, N=99)$ =5.6 | .050 | .24 |

[+] The format is $\chi^2$(degrees of freedom, N) =chi-square statistics

[++] Significance value

[+++] Effect size

The chi-square test for independence indicated that the PV and VP sequences only represented two different populations for Questions 4 and 5. For these questions, students in the VP sequence were more likely to provide responses that aligned with the ideal physical relationships. For example, in Question 4, students in the VP sequence were more likely to respond that work was the same (after the virtual experiment) or nearly the same (after both experiments) across pulley systems than were students in the PV sequence. On the other hand, students in the PV sequence were more likely to respond that work got easier as the pulley system got more complex. In Question 5, students in the VP sequence were more likely to respond that work and potential energy were the same (or that the work increased for the double compound due to an error in the simulation) for both contrasts. On the other hand, students in the PV sequence were more likely to respond that work changed and potential energy did not after the physical experiment. While this response correctly describes the behavior of work and potential energy that they observed, it does not draw a comparison between the values, as requested in the question. Possible learning theories of learning with which these results align are discussed in Section 5.4.

## 5.4 Trends and Discussion

The major trend that emerged from the pulley worksheet analysis was the manipulative and sequence dependence of responses to the analysis questions about work and potential energy (WQ4 and WQ5). In each of the three studies, students in the VP sequence were more likely to provide responses that aligned with the ideal (friction-free) relationships than were students in the PV sequence. For example, on Question 4, students in the VP sequence were more likely to respond that work was the same or similar across pulley systems, while students in the VP sequence were more likely to respond that work changed across pulley systems. On Question 5, students in the VP sequence were more likely to provide a response that adequately addressed the comparison required by the question (i.e. work is similar to potential energy) than were students in the PV sequence, who were more likely to discuss work and potentially separately or describe them as unrelated.

Chinn and Brewer (1993) have described the possible responses one can have towards anomalous data, or data that does not fit the individual’s existing theory. They explain that properties of the data may affect the stance one takes towards that data. For example, data that is not viewed as credible can be easily rejected and ambiguous data can be easily reinterpreted. In the VP sequence, students are first presented with data that is easily interpreted to indicate that (in the absence of friction) the work required to lift an object does not vary between pulley systems. Students in the VP sequence are likely to develop, at least tentatively, the idea that the work does not change. Students in the PV sequence, however, are presented with ambiguous data in the physical experiment due to fluctuations in the work values. Thus, students may reinterpret this data to fit their existing theory that a more complicated pulley system should require less work.

Schwartz *et al.* (2008) have described how the learning environment can support dynamic transfer, or the creation of new conceptions. The environment may allow for distributed memory, afford alternative interpretations and feedback, offer candidate structures, or provide a focal point for coordination. This framework is applied to students’ experiences with the physical and virtual manipulatives more explicitly in Chapter 9. However, this framework may also explain why students in the VP sequence were better prepared than students in the PV sequence to make the comparison between work and potential energy required in Question 5. In the simulation, work was represented as both a number and a bar graph. This graph may provide a "focal point for coordination" to help students make comparisons.

Overall, the worksheet analysis seems to indicate that the physical and virtual manipulatives equally support students' understanding of force and mechanical advantage. However, the virtual experiment seems to better support students' understanding of work and potential energy. Students in the VP sequence provide more productive responses about work and potential energy in both the virtual and physical experiments.

# CHAPTER 6 - Pulley Studies: Test Analysis

In this chapter, I present the quantitative analysis of students' performance on the conceptual tests in the pulley studies. I present the results for each study and then discuss trends across the three studies. Refer to Section 4.2 for a complete description of how each study was conducted. These results help to address Research Question 1, specifically the questions:

- What do students learn from the physical activities, and what do they learn from the virtual activities?
- When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity?
- When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other?

The statistical analysis was conducted with the assistance of Dr. Leigh Murray and Zhining Ou of the Kansas State University Statistics Department. For each study, a mixed ANOVA was used to analyze students' performance on the tests. Refer to Section 3.4.4 for a more complete description of the statistical analyses performed.

## 6.1 Pulley Study #1: PWS09

For this analysis, students' test scores were calculated from the eleven multiple-choice questions on the test used in the PWS09 study. These questions are described in Table 4.3 in Section 4.2.1.3, and the test is included in Appendix C. We performed analyses on the overall score, as well as concept sub-scores for force (four questions), work/energy (four questions), and mechanical advantage (two questions).

The PWS09 study involved two treatments. All students used both physical and virtual manipulatives to perform experiments with pulleys. However, some students used the manipulatives in the physical-virtual (PV) sequence, while others used the manipulatives in the virtual-physical (VP) sequence.

Each score was analyzed with a mixed ANOVA. Laboratory section and treatment were used as between-subjects factors, and test score (at the levels pre-test, mid-test and post-test) was used as a within-subjects factor. The main effect ("Test") explains whether scores changed among the pre-test, mid-test and post-test, regardless of treatment. The interaction effect

(“Test*Treat”) explains whether the way students’ scores changed depended on the treatment (i.e. the sequence in which they performed the physical and virtual experiments.)

### *6.1.1 Total Score*

Figure 6.1 displays the mean pre-test, mid-test and post-test scores for the total score for students in the physical-virtual (PV) and virtual-physical (VP) sequences. Students could earn up to a maximum of eleven points for the total score, one point for each multiple-choice question. Students in both sequences began with similar pre-test mean total scores ($PV_{pre}$=3.8, S.E.=0.3; $VP_{pre}$=3.6; S.E.=0.2). Students completed the mid-test after performing one set of activities; students in the PV sequence had performed the physical experiment, while students in the VP sequence had performed the virtual experiment. At the mid-test, students appear to perform similarly ($PV_{mid}$=6.1, S.E.=0.3; $VP_{mid}$=6.3, S.E.=0.3). Students completed the post-test after performing both sets of activities. On the post-test, the mean score for the PV sequence was slightly higher than the mean score for the VP sequence ($PV_{post}$=7.3, S.E.=0.3; $VP_{post}$=6.6, S.E.=0.4).

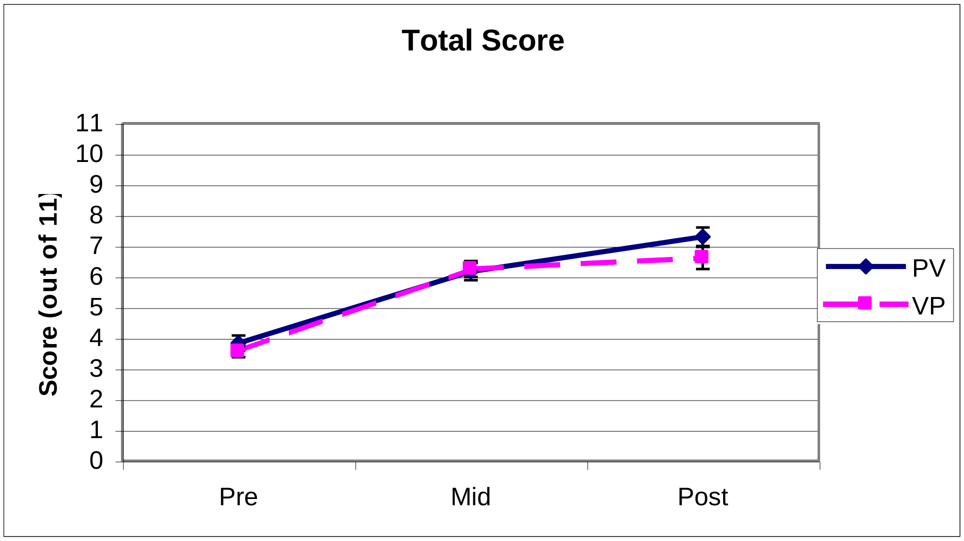


**Figure 6.1 Physical World Spring 2009 Test Scores: Total.**

The main effect of test was significant, *F*(2, 260)=137.4, p<.001. Students’ total scores increased significantly from pre-test to mid-test, *F*(1, 260)=161.3, p<.001, r=0.62, from pre-test to post-test, *F*(1, 260)=243.4, p<.001, r=0.70, and from mid-test to post-test, *F*(1, 260)=8.4, p=.012, r=0.18. This indicates that students learned about the physics of pulleys in both the first and second activities. The interaction of treatment with test was also significant, *F*(2, 260)=3.2, p=.044. The difference in how students' scores changed in the two sequences was only statistically significant from mid-test to post-test, *F*(1, 260)=6.2, p=.013, r=0.15, and not from pre-test to mid-test, *F*(1, 260)=2.3, p=.134, r=0.09, or from pre-test to post-test, *F*(1, 260)=1.0, p=.321, r=0.6. Figure 6.1 above shows that students in the PV sequence continued to learn in the second (virtual) activity, while students in the VP sequence do not appear to learn additional concepts in the second (physical) activity. The force, work and mechanical advantage scores were analyzed to determine if a specific concept led to the difference in performance between the two sequences at the mid-test.

### *6.1.2 Force Sub-score*

Figure 6.2 below displays the mean pre-test, mid-test and post-test scores for the force sub-score for the PV and VP sequences. Students could earn up to a maximum of four points for the force sub-score, one point for each multiple-choice question related to force. Students in both sequences began with similar mean force pre-test scores ($PV_{pre}$=1.2, S.E.=0.1; $VP_{pre}$=1.0, S.E.=0.1). After performing the first set of activities, students in the PV sequence had a slightly higher mean force mid-test score than students in the VP sequence ($PV_{mid}$=2.8, S.E.=0.1; $VP_{mid}$=2.3, S.E.=0.2). After performing both sets of activities, students in the PV sequence still slightly outperformed students in the VP sequence ($PV_{post}$=2.9, S.E.=0.1; $VP_{post}$=2.4, S.E.=0.2).

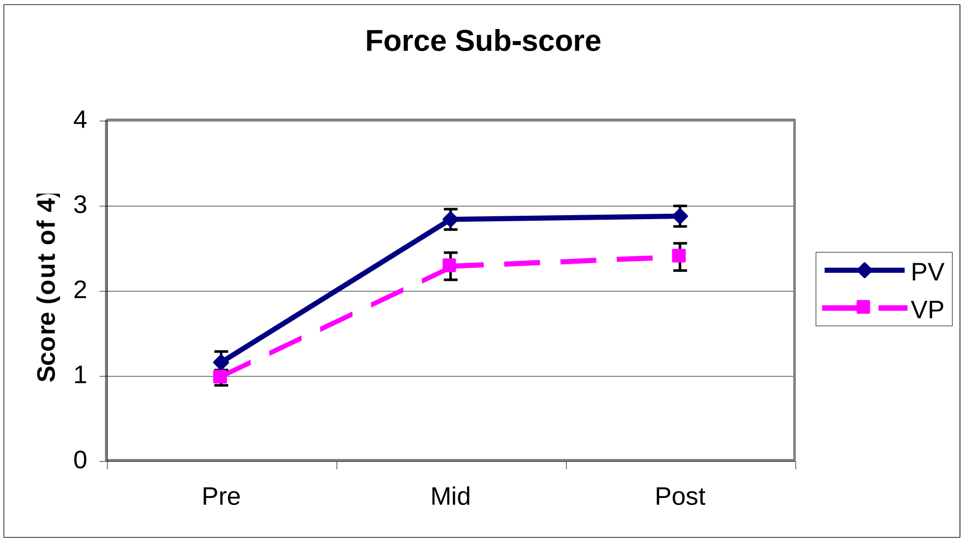


**Figure 6.2. Physical World Spring 2009 Test Scores: Force Sub-score.**

The main effect of test was significant, *F*(2, 260)=147.4, p<.001. Students' scores increased significantly from pre-test to mid-test, *F*(1, 260)=210.2, p<.001, r=0.67, and from pre-test to post-test, *F*(1, 260)=231.0, p<.001, r=0.69. However, the scores did not increase significantly from mid-test to post-test, *F*(1, 260)=0.6, p=1.00, r=0.05. This indicates that students only learned about force from the first activity. The interaction of treatment with test was not significant, *F*(2, 260)=1.8, p=.176. This indicates students' scores did not change differently in the two sequences.

This result is somewhat surprising. One might expect students to learn more about force from the physical experiment since the physical manipulative provides students the kinesthetic experience of feeling the force needed to lift the load. However, the results from the conceptual test indicate the physical and virtual manipulative support students' understanding of force equally. In both the PV and VP sequences, students force sub-scores only increased as a result of the first activity and not as a result of the second activity. However, there is room for improvement in the mean post-test force sub-score in both sequences. This may suggest that neither the physical nor virtual activity is fully preparing students for the force questions on the conceptual test.

### *6.1.3 Work/Energy Sub-score*

Figure 6.3 below displays the mean pre-test, mid-test and post-test scores for the work/energy sub-score for the PV and VP sequences. Students could earn up to a maximum of four points for the work/energy sub-score, one point for each multiple-choice question related to work or potential energy. Students in both sequences began with similar mean pre-test work/energy scores ($PV_{pre}$=2.0, S.E.=0.1; $VP_{pre}$=2.0, S.E.=0.1). After performing the first set of activities, the mean scores for the two sequences diverged ($PV_{mid}$=1.5, S.E.=0.2; $VP_{mid}$=2.8, S.E.=0.1). While the mean score increased from pre-test to mid-test for the VP sequence, it actually decreased from pre-test to mid-test for the PV sequence. The work/energy score was closer at the post-test for the two sequences, though the students in the VP sequence still had slightly higher scores ($PV_{post}$=2.4, S.E.=0.2; $VP_{post}$=2.8, S.E.=0.2).

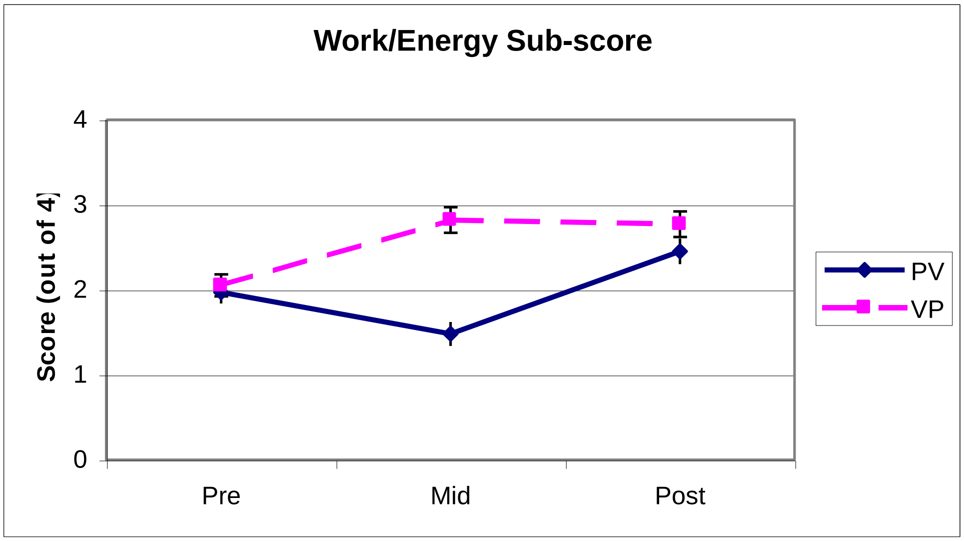


**Figure 6.3. Physical World Spring 2009 Test Scores: Work/Energy Sub-score**

The main effect of test was significant, *F*(2, 260)=15.7, p<.001. Students' scores increased significantly from pre-test to post-test, *F*(1, 260)=29.2, p<.001, r=0.32, and mid-test to post-test, *F*(1, 260)=16.8, p<.001, r=0.25. However, scores did not change significantly from pre-test to mid-test, *F*(1, 260)=1.4, p=.651, r=0.07. This indicates that students mostly learned about work and potential energy in the second experiment. The interaction of treatment with test was significant, *F*(2, 260)=17.9, p<.001. Students' scores changed differently in the two sequences from pre-test to mid-test, *F*(1, 260)=31.8, p<.001, r=0.33, and from mid-test to post-test, *F*(1, 260)=20.7, p<.001, r=0.27. However, scores did not change differently from pre-test to post-test, *F*(1, 260)=1.2, p<.001, r=0.07. This indicates that the specific manipulatives differently supported students' learning of work and potential energy, but the two sequences supported this concept equally.

It is not surprising that the simulation better supported students' understanding of work and potential energy. Work and potential energy are abstract concepts and cannot be directly observed in the physical experiment. The simulation presents information about work and potential energy in multiple representations, both numerically and graphically. In addition, the data from the simulation is free of frictional effects so students can clearly see the ideal nature of work and potential energy. On the other hand, friction in the physical experiment may make it difficult for students to answer questions about ideal situations on the conceptual test.

### *6.1.4 Mechanical Advantage Sub-score*

Figure 6.4 below displays the pre-test, mid-test and post-test means for the mechanical advantage sub-score for the PV and VP sequences. Students could earn up to a maximum of two points for the mechanical advantage sub-score, one point for each question related to mechanical advantage. The two sequences began with similar mechanical advantage pre-test scores ($PV_{pre}$=0.4, S.E.=0.1; $VP_{pre}$=0.2, S.E.=0.1). Scores in both sequences improved similarly at the mid-test ($PV_{mid}$=1.1, S.E.=0.1; $VP_{mid}$=0.8, S.E.=0.1) and the post-test ($PV_{post}$=1.2, S.E.=0.1; $VP_{post}$=0.8, S.E.=0.1).

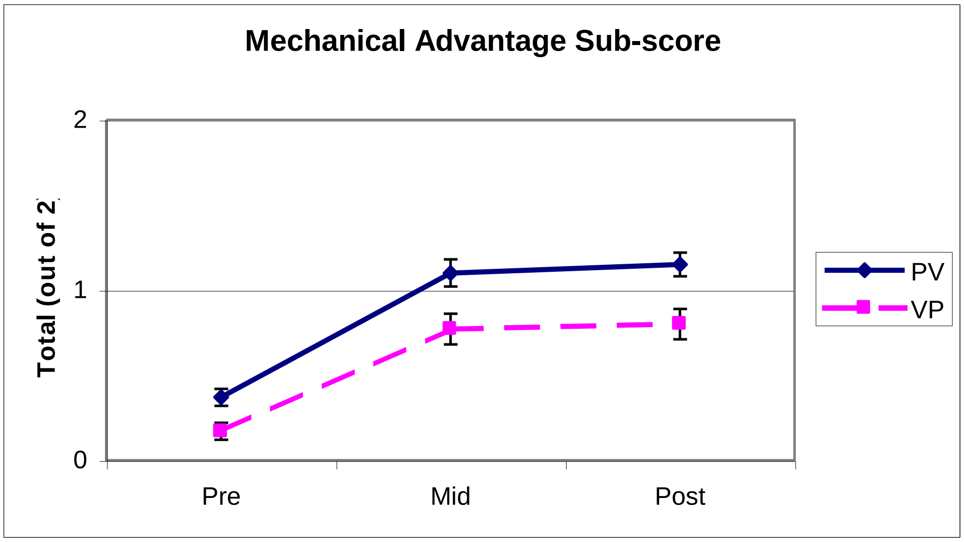


**Figure 6.4. Physical World Spring 2009 Test Scores: Mechanical Advantage Sub-score.**

The main effect of test was significant, *F*(2, 260)=98.6, p<.001. Students' scores increased significantly from pre-test to mid-test, *F*(1, 260)=139.2, p<.001, r=0.59, and pre-test to post-test, *F*(1, 260)=156.3, p<.001, r=0.61. However, scores did not change significantly from mid-test to post-test, *F*(1, 260)=0.6, p=1.00, r=0.05. This indicates that students only learned about mechanical advantage from the first activity. The interaction of treatment with test was not significant, *F*(2, 260)=1.0, p=.372. This indicates that students' scores did not change differently in the two sequences.

It is not necessarily surprising that the physical and virtual manipulatives offered equal support for students' understanding of mechanical advantage. Arguments can be made in favor of both the physical and virtual manipulatives in the case of mechanical advantage. For example, mechanical advantage is closely related to the applied force needed to lift the load, which the physical experiment allows students to experience physically. However, mechanical advantage is a more abstract concept than force since it is based on a calculation. The simulation, with its ideal (i.e. frictionless) conditions and multiple representations (i.e. numerical results and bar charts), may better help students learn abstract concepts and generalize to friction-free environments. Since neither manipulative supported students' learning about mechanical advantage more than the other, it is possible that the advantages of each balanced. Also, since the mean score increased less than one point in both sequences, it is possible that neither manipulative offered much support for students' learning about mechanical advantage.

### *6.1.5 Summary of Results*

Students in the PWS09 study performed experiments with both physical and virtual manipulatives, either in the PV or VP sequence. This study helps to address Research Question 1, which focuses on what students learn from the physical and virtual manipulatives. Specifically, the pre-test, mid-test, post-test design allows for comparison of the physical and virtual manipulatives, comparison of the PV and VP sequences, and judgment of the usefulness of performing the same activity twice with the two different manipulatives. A summary of results of the mixed ANOVA is shown in Table 6.1 below.

**Table 6.1 Summary of PWS09 Test Statistics**

| **Score** | | **F-test** | | **Pre/Mid Contrast** | | **Mid/Post Contrast** | | **Pre/Post Contrast** | |
|---|---|---|---|---|---|---|---|---|---|
| | **Effect** | ***F*** | **p** | ***F*** | **p** | ***F*** | **p** | ***F*** | **p** |
| **Total** | **Test** | *F*(2, 260)= 137.4 | <.001 | *F*(1, 260)= 161.3 | <.001 | *F*(1, 260)= 8.4 | .012 | *F*(1, 260)= 243.4 | <.001 |
| | **Test* Treat** | *F*(2, 260)= 3.2 | .044 | *F*(1, 260) = 2.3 | .134 | *F*(1, 260)= 6.2 | .013 | *F*(1, 260) =1.0 | .321 |
| **Force** | **Test** | *F*(2, 260)= 147.4 | <.001 | *F*(1, 260)= 210.2 | <.001 | *F*(1, 260)= 0.6 | 1.00 | *F*(1, 260)= 231.0 | <.001 |
| | **Test* Treat** | *F*(2, 260)= 1.8 | .176 | | | | | | |
| **WE** | **Test** | *F*(2, 260)= 15.7 | <.001 | *F*(1, 260)= 1.4 | .651 | *F*(1, 260)= 16.8 | <.001 | *F*(1, 260)= 29.2 | <.001 |
| | **Test* Treat** | *F*(2, 260)= 17.9 | <.001 | *F*(1, 260) = 31.8 | <.001 | *F*(1, 260)= 20.7 | <.001 | *F*(1, 260) =1.2 | .281 |
| **MA** | **Test** | *F*(2, 260)= 98.6 | <.001 | *F*(1, 260)= 139.2 | <.001 | *F*(1, 260)= 0.6 | 1.00 | *F*(1, 260)= 139.2 | <.001 |
| | **Test* Treat** | *F*(2, 260)= 1.0 | .372 | | | | | | |

The results indicate that students only learned about force and mechanical advantage from the first activity they performed, since the mid-test/post-test contrasts were not significant for these sub-scores. However, students appear to have learned more about work and potential energy in the second activity, since the pre-test/mid-test contrast was not significant. The mean total score increased across all three tests, as each contrast was significant. The physical and virtual manipulatives, and PV and VP sequences, appear to offer equal support for students' learning about force and mechanical advantage, as the interaction was not significant for these sub-scores. However, the virtual manipulative appears to better support students' understanding of work and potential energy, since the interaction effect was significant and Figure 6.3 shows students' work/energy scores increased when they performed the virtual activity. Overall, the PV and VP sequences seem to offer equal support for students' understanding of work and potential energy, since the pre-test/post-test interaction contrast was not significant.

This study supports the idea that students' learning about work and potential energy is better supported by the virtual manipulative. This may be due to the multiple representations used to present data or the ideal conditions in the simulation. However, this study does not find support for the idea that the physical manipulative better supports students' learning about force. Both manipulatives equally supported students' learning about force and neither activity sequence seems to have helped students develop all of the understanding needed to answer the force, work/energy or mechanical advantage questions. This suggests students may need more scaffolding to learn about these concepts than is provided by the physical and virtual activities.

## 6.2 Pulley Study #2: PWF09

For this analysis, students' test scores were calculated from the twenty multiple-choice questions on the test used in the PWF09 study. These questions are described in Table 4.6 in Section 4.2.2.3 and the test is included in Appendix G. We performed analyses on the overall score, as well as concept sub-scores for force (seven questions), work/energy (nine questions), and mechanical advantage (three questions).

As in the PWS09 study, the PWF09 study involved two treatments. All students used both physical and virtual manipulatives to perform experiments with pulleys. However, some students used the manipulatives in the physical-virtual (PV) sequence, while others used the manipulatives in the virtual-physical (VP) sequence.

Also as in the PWS09 study, each score was analyzed with a mixed ANOVA. Laboratory section and treatment were used as between-subjects factors, and test score (at the levels pre-test, mid-test and post-test) was used as a within-subjects factor. The main effect ("Test") explains whether scores changed among pre-test, mid-test and post-test, regardless of treatment. The interaction effect ("Test*Treat") explains whether the way students' scores changed depended on the treatment (i.e. the sequence in which they performed the physical and virtual experiments.)

### *6.2.1 Total Score*

Figure 6.5 below displays the pre-test, mid-test and post-test results for the overall score for students in the physical-virtual (PV) and virtual-physical (VP) sequences. Students could earn up to a maximum of twenty points for the total score, one point for each multiple-choice question on the test. The two sequences began with similar mean pre-test total scores ($PV_{pre}$=10.1, S.E.=0.4; $VP_{pre}$=9.8, S.E.=0.4). Students completed the mid-test after performing the first activity, so students in the PV sequence had used the physical equipment, while students in the VP sequence had used the computer simulation. On the mid-test, the mean score for the VP sequence was higher than the mean score for the PV sequence ($PV_{mid}$=12.3, S.E.=0.3; $VP_{mid}$=13.9, S.E.=0.4). Students completed the post-test after performing both activities. On the post-test, the total mean scores were again similar for the two sequences ($PV_{post}$=13.7, S.E.=0.4; $VP_{post}$=13.9, S.E.=0.4).

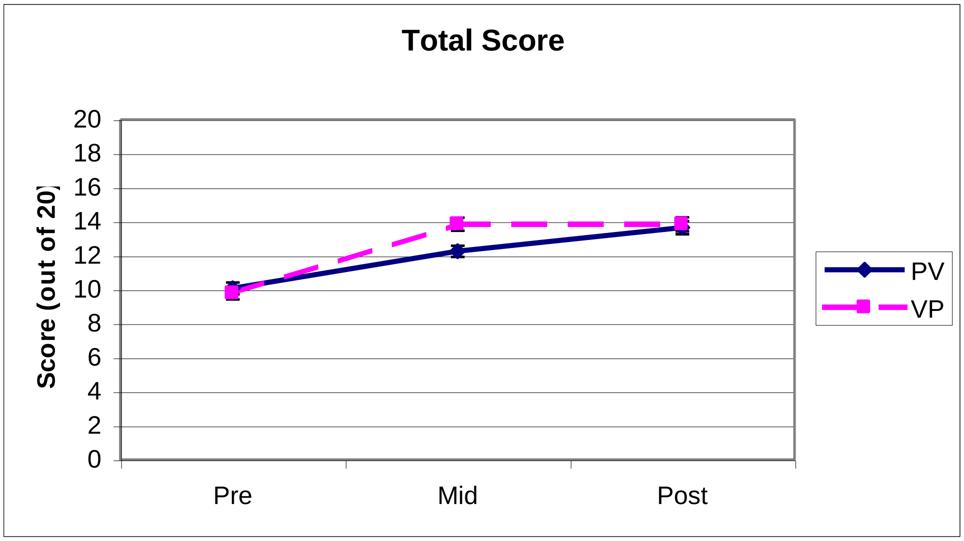


**Figure 6.5 Physical World Fall 2009 Test Scores: Total.**

The main effect of test was significant, *F*(2, 246)=133.1, p<.001. Students' scores increased significantly from pre-test to mid-test, *F*(1, 246)=156.2, p<.001, r=0.62, pre-test to post-test, *F*(1, 246)=-15.2, p<.001, r=0.70, and mid-test to post-test *F*(1, 246)=7.8, p=.017, r=0.18. This indicates that students learned from both the first and second activities they performed. The interaction of treatment with test was also significant, *F*(1, 246)=14.4, p<.001. The interaction was significant from pre-test to mid-test *F*(1, 246)=14.4, p<.001, r=0.24, and mid-test to post-test, *F*(1, 246)=7.8, p=.006, r=0.18. However, the interaction was not significant from pre-test to post-test, *F*(1, 246)=1.0, p=.315, r=0.06. Figure 6.5 shows that the mean total score increased across all three tests in the PV sequence, but only increased from pre-test to mid-test in the VP sequence. Thus, it appears students mainly learned from the virtual activity in the VP sequences but learned from both activities in the PV sequence. The force, work/energy and mechanical advantage sub-scores were analyzed to explore whether a specific concept led to the difference in performance between the PV and VP sequences.

### *6.2.2 Force Sub-score*

Figure 6.6 below displays the mean pre-test, mid-test and post-test force sub-scores from the PV and VP sequences. Students could earn up to a maximum of seven points for the force sub-score, one point for each question related to force. The two sequences began with similar mean force scores ($PV_{pre}$=3.7, S.E.=0,2; $VP_{pre}$=3.6, S.E.=0.2). On the mid-test, the force scores increased similarly for both sequences ($PV_{mid}$=5.3, S.E.=0.2; $VP_{mid}$=5.1, S.E.=0.1). On the post-test, the mean score increased slightly for the PV sequence, but decreased slightly for the VP sequence ($PV_{post}$=5.4, S.E.=0.2; $VP_{post}$=4.9, S.E.=0.2).

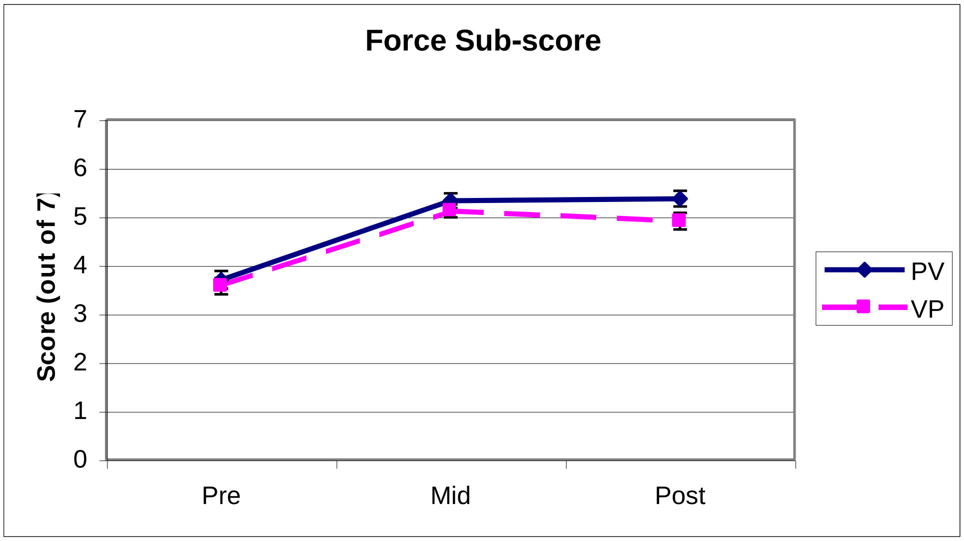


**Figure 6.6 Physical World Fall 2009 Test Scores: Force Sub-score.**

The main effect of test was significant, *F*(2, 246)=86.5, p<.001. Students' scores increased significantly from pre-test to mid-test, *F*(1, 246)=136.9, p<.001, r=0.60, and from pre-test to post-test, *F*(1, 246)=123.2, $p<.001$, r=0.58. However, scores did not change significantly from mid-test to post-test, *F*(1, 246)=0.4, p=1.00, r=0.04. This indicates that students only learned about force from the first activity. The interaction of treatment with test was not significant, *F*(2, 246)=0.8, p=.455. This indicates students' force sub-scores did not change differently in the two sequences.

As in the PWS09 pulley study, students' force sub-scores did not depend on the manipulative or manipulative sequence in the PWF09 study. As discussed above, this result is surprising because the physical manipulative provides students with the kinesthetic experience of feeling the change in the applied force needed to lift the load with different pulley setups. One might expect the kinesthetic experience to better support students' learning about force than the simulation, but the results indicate the physical and virtual manipulatives equally supported students' understanding of force. There is still room for students' force sub-scores to improve in both the PV and VP sequences as the mean post-test scores were less than 5.5 points out of a possible seven points. However, students' scores did not increase significantly after the second activity in either sequence. This suggests students may need additional scaffolding to continue to learn about force.

### *6.2.3 Work/energy Sub-score*

Figure 6.7 below displays the mean pre-test, mid-test and post-test scores for the work/energy sub-score for the PV and VP sequences. Students could earn up to a maximum of nine points for the work/energy sub-score, one point for each question related to work or potential energy. The two sequences began with similar mean work/energy scores ($PV_{pre}$=4.8, S.E.=0.2; $VP_{pre}$=4.8, S.E.=0.2). However, after students completed the first activity, the mean score increased on the mid-test for the VP sequence, but decreased for the PV sequence ($PV_{mid}$=4.3, S.E.=0.2; $VP_{mid}$=6.1, S.E.=0.2). After students completed the second activity, the mean score increased for the PV sequence and remained the same for the VP sequence ($PV_{post}$=5.5, S.E.=0.2; $VP_{post}$=6.1, SE=0.3); the VP mean score was still slightly higher than the PV mean score on the post-test.

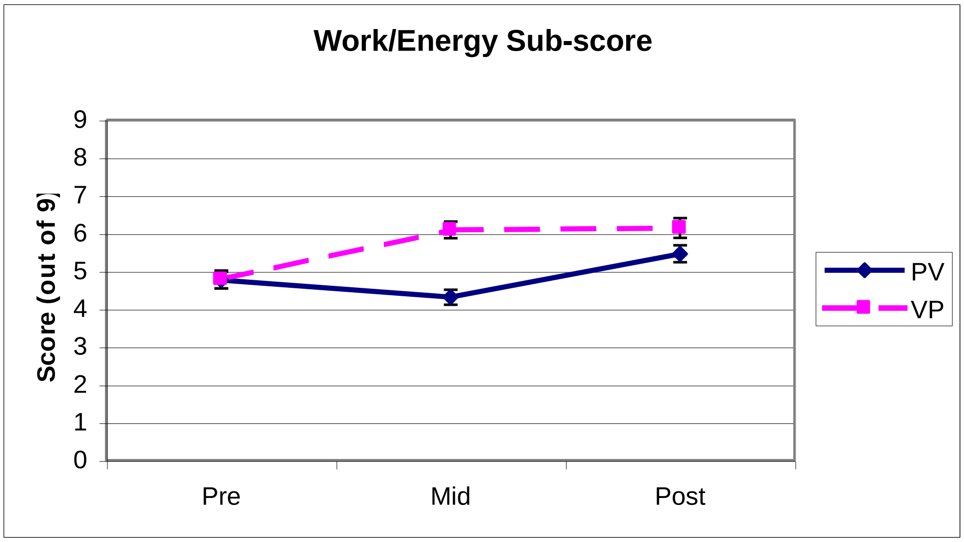


**Figure 6.7 Physical World Fall 2009 Test Scores: Work/Energy Sub-score.**

The main effect of test was significant, *F*(2, 246)=18.0, p<.001. Students' scores increased significantly from pre-test to mid-test, *F*(1, 246)=-2.6, p=.031, r=0.16, from pre-test to post-test, *F*(1, 246)=36.0, p<.001, r=0.36, and from mid-test to post-test *F*(1, 246)=11.6, p=.002, r=0.21. This indicates that students learned about work and potential energy in both the first and second pulley activities. The interaction of treatment with test was also significant, *F*(2, 246)=12.8, p<.001. Students' scores in the two sequences changed differently from pre-test to mid-test, *F*(1, 246)=25.2, p<.001, r=0.30, and from mid-test to post-test, *F*(1, 246)=9.6, p=.002, r=0.19. However, students' scores did not change differently from pre-test to post-test, *F*(1, 246)=3.7, p=.056, r=0.12. Figure 6.7 shows that the work/energy mean score increased from pre-test to mid-test in the VP sequence, but decreased from pre-test to mid-test in the PV sequence. Then, the mean increased from mid-test to post-test in the PV sequence and stayed constant in the VP sequence. Overall, students' scores change similarly from pre-test to post-test in both sequences.

As in the PWS09 study, the virtual manipulative appears to provide better support than the physical manipulative for students' learning about work and potential energy in the PWF09 study. As discussed previously, it is not surprising that the simulation better supports students' understanding of work and energy for several reasons. First, the simulation used multiple representations to present data about work and energy; the results are presented both numerically and graphically. Second, the simulation allows students to explore the pulley systems in idealized (i.e. frictionless) conditions, which makes the idealized relationships between work and potential energy more apparent than in the physical experiment. In both sequences, there is room for improvement in students' work/energy sub-scores at the post-test, which indicates students may need additional support to further develop their understanding of work and potential energy.

### *6.2.4 Mechanical Advantage Sub-score*

Figure 6.8 below displays the mean pre-test, mid-test and post-test mechanical advantage sub-scores for the PV and VP sequences. Students could earn up to a maximum of three points for the mechanical advantage sub-score, one point for each question related to mechanical advantage. The two sequences began with similar pre-test mechanical advantage scores ($PV_{pre}$=1.2, S.E.=0.1; $VP_{pre}$=1.2, S.E.=0.1). The mechanical advantage scores increased similarly for the two sequences on the mid-test ($PV_{mid}$=2.0, S.E.=0.1; $VP_{mid}$=1.9, S.E.=0.1) and the post-test ($PV_{post}$=2.1, S.E.=0.1; $VP_{post}$=2.1, S.E.=0.1).

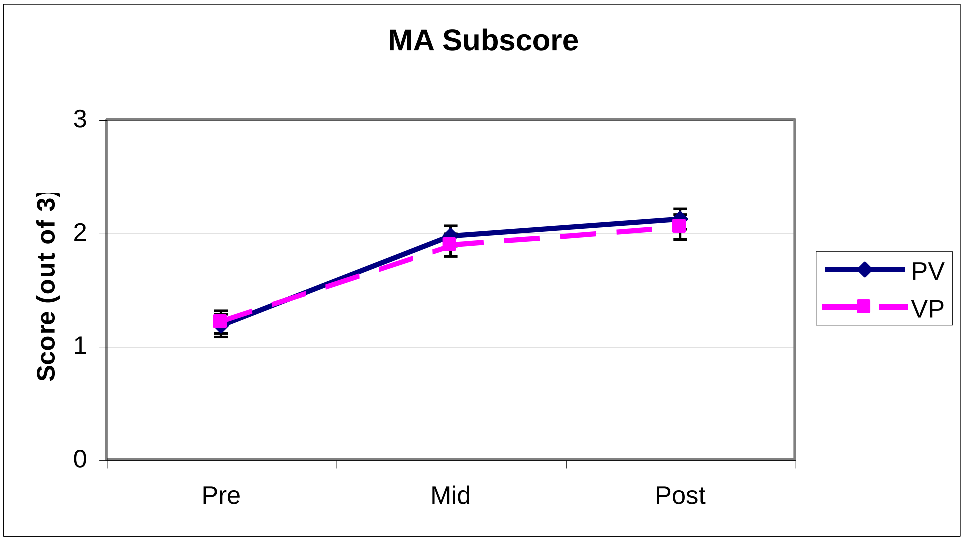


**Figure 6.8 Physical World Fall 2009 Test Scores: Mechanical Advantage Sub-score.**

The main effect of test was significant, *F*(2, 246)=91.1, p<.001. Students' scores increased significantly from pre-test to mid-test, *F*(1, 246)=108.2, p<.001, r=0.55, and from pre-test to post-test, *F*(1, 246)=161.3, p<.001, r=0.63. However, scores did not change significantly from mid-test to post-test, *F*(1, 246)=5.3, p=.070, r=0.15. This indicates that students only learned about mechanical advantage in the first activity. The interaction of treatment with test was not significant, *F*(2, 246)=0.4, p=.672. This indicates that students' scores did not change differently in the two sequences.

As in the PWS09 pulley study, the two manipulatives and two sequences appear to offer equal support for students' understanding of mechanical advantage. This is not surprising as both manipulatives offer unique forms of support for mechanical advantage. Since mechanical advantage is closely related to force, the kinesthetic experience of feeling force in the physical experiment offers one type of support. However, since mechanical advantage is also a somewhat abstract concept, the multiple representations (i.e. numerical and graphical) in the simulation offer another kind of support for students' understanding.

### *6.2.5 Summary of Results*

Students in the PWF09 pulley study performed both physical and virtual activities, but in different sequences. This study design allows for exploration of the comparative effectiveness of the physical and virtual experiments, the added benefit of performing both types of experiments, and the comparative effectiveness of the physical-virtual and virtual-physical sequences. A summary of results of the mixed ANOVA is shown in Table 6.2 below.

**Table 6.2 Summary of PWF09 Test Statistics**

| **Score** | | **F-test** | | **Pre/Mid Contrast** | | **Mid/Post Contrast** | | **Pre/Post Contrast** | |
|---|---|---|---|---|---|---|---|---|---|
| | **Effect** | ***F*** | **p** | ***F*** | **p** | ***F*** | **p** | ***F*** | **p** |
| **Total** | **Test** | *F*(2, 246)= 133.1 | <.001 | *F*(1, 246)= 156.2 | <.001 | *F*(1, 246)= 7.8 | .017 | *F*(1, 246)= 231.0 | .001 |
| | **Test*Trt** | *F*(2, 246)= 7.7 | <.001 | *F*(1, 246)= 14.4 | <.001 | *F*(1, 246)= 7.8 | .006 | *F*(1, 246)=1.0 | .315 |
| **Force** | **Test** | *F*(2, 246)= 86.5 | <.001 | *F*(1, 246)= 136.9 | <.001 | *F*(1, 246)= 0.4 | 1.00 | *F*(1, 246)= 123.2 | <.001 |
| | **Test*Trt** | *F*(2, 246)= 0.8 | .455 | | | | | | |
| **WE** | **Test** | *F*(2, 246)= 18.0 | <.001 | *F*(1, 246)= 6.8 | .031 | *F*(1, 246)= 11.6 | .002 | *F*(1, 246)= 36.0 | <.001 |
| | **Test*Trt** | *F*(2, 246)= 12.8 | <.001 | *F*(1, 246)= 25.2 | <.001 | *F*(1, 246)= 9.6 | .002 | *F*(1, 246)=3.7 | .056 |
| **MA** | **Test** | *F*(2, 246)= 91.1 | <.001 | *F*(1, 246)= 108.2 | <.001 | *F*(1, 246)= 5.0 | .070 | *F*(1, 246)= 161.3 | <.001 |
| | **Test*Trt** | *F*(2, 246)= 0.4 | .672 | | | | | | |

The results indicate that students only learned about force and mechanical advantage in the first activity, since the mid-test/post-test contrast was not significant for these sub-scores. However, they continued to learn about work and potential energy in the second activity, as this mid-test/post-test contrast was significant. The physical and virtual manipulatives offer equal support for students' learning about force and mechanical advantage since the interaction effect was not significant for these sub-scores. However, the simulation appears to offer better support for students' learning about work and potential energy than the physical equipment, as this interaction effect was significant. The PV and VP sequences offered similar support for students' overall learning and for their learning about the specific concepts of force, work/energy and mechanical advantage, as none of the pre-test/post-test interaction contrasts were significant.

The PWF09 pulley study confirms the results of the PWS09 pulley study. It again finds support that the virtual manipulative offers better support for students' learning about work and potential energy. This may be due to the multiple representations used to present data or to the ideal conditions in the simulation. Also, this study confirms the PWS09 result that the physical and virtual manipulatives provide equal support for students' learning about force and mechanical advantage and that the PV and VP sequences overall provide equal support for students' learning.

## 6.3 Pulley Study #3: CoPF09

For this analysis, students' test scores were calculated from the twenty multiple-choice questions on the test used in the CoPF09 study. These questions are described in Table 4.9 in Section 4.2.3.3 and the test is included in Appendix K. We performed analyses on the overall score, as well as concept sub-scores for force (seven questions), work/energy (nine questions), and mechanical advantage (three questions).

As in previous pulley studies, the CoPF09 study involved two treatments. All students used both physical and virtual manipulatives to perform experiments with pulleys. However, some students used the manipulatives in the physical-virtual (PV) sequence, while others used the manipulatives in the virtual-physical (VP) sequence. In the CoPF09 study, students chose the order in which they used the manipulatives.

Each score was analyzed with a mixed ANOVA. Treatment was used as a between-subjects factor, and test score (at the levels pre-test, mid-test and post-test) was used as a within-subjects factor. The main effect ("Test") explains whether scores changed among the pre-test, mid-test and post-test, regardless of treatment. The interaction effect ("Test*Treat") explains whether the way students' scores changed depended on the treatment (i.e. the sequence in which they performed the physical and virtual experiments.)

### *6.3.1 Total Score*

Figure 6.9 below displays the pre-test, mid-test and post-test results for the overall score for students in the physical-virtual (PV) and virtual-physical (VP) sequences. Students could earn up to a maximum of twenty points for the total score, one point for each multiple-choice question on the test. As shown in Figure 6.9, the scores evolved quite similarly in both sequences. The two sequences began with similar pre-test total scores ($PV_{pre}$=7.9, S.E.=0.3; $VP_{pre}$=8.6, S.E.=0.4). Scores in both sequences increased on the mid-test after students completed the first activity ($PV_{mid}$=11.1, S.E.=0.4; $VP_{mid}$=11.9, S.E.=0.4). At the mid-test, students in the PV sequence had completed only the physical activity, while students in the VP sequence had completed only the virtual activity. The mean scores stayed consistent on the post-test in both sequences ($PV_{post}$=11.0, S.E.=0.5; $VP_{post}$=11.8, S.E.=0.5). At the post-test, students in both sequences had completed both the physical and virtual activities.

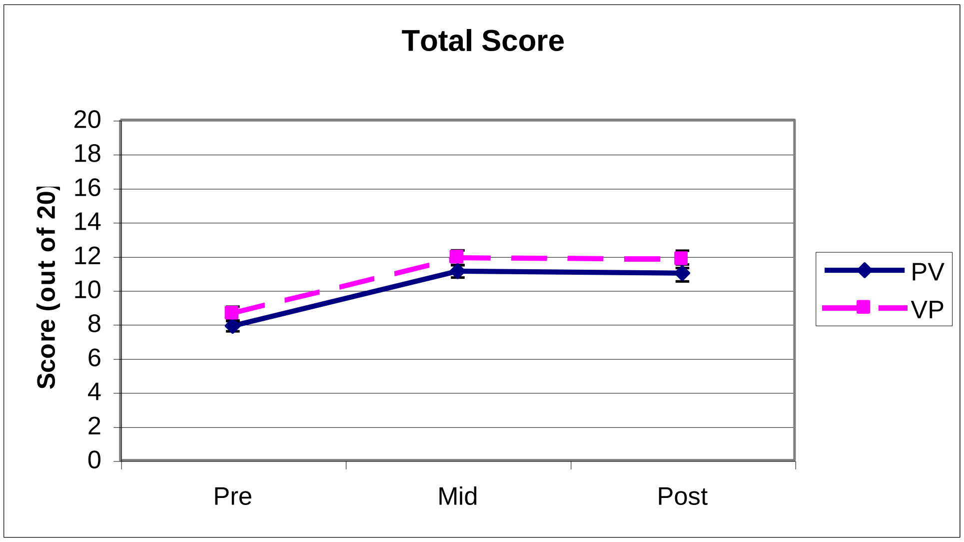


**Figure 6.9 Concepts of Physics Fall 2009 Test Scores: Total**

The main effect of test was significant, *F*(2, 196)=56.8, p<.001. The planned contrasts revealed students' scores changed significantly from pre-test to mid-test, *F*(1, 196)=88.4, p<.001, r=0.56, and pre-test to post-test, *F*(1, 196)=82.8, p<.001, r=0.54. However, scores did not change significantly from mid-test to post-test, *F*(1, 196)=0.1, p=1.00, r=0.02. This indicates that students learned about the physics of pulleys during the first activity, but seem not to have learned additional ideas from the second activity. The interaction of treatment with test was not significant, *F*(2, 196)=0.01, p=.990. This indicates that students' overall learning was similar in the PV and VP sequences. The force, work/energy and mechanical advantage sub-scores were analyzed to explore whether the manipulatives also offered equal support for students' understanding of these specific concepts.

### *6.3.2 Force Sub-score*

Figure 6.10 below displays the mean pre-test, mid-test and post-test scores for the force sub-score for the PV and VP sequences. Students could earn up to a maximum of seven points on the force sub-score, one point for each question related to force. The two sequences began with similar mean force pre-test scores ($PV_{pre}$=3.1, S.E.=0.2; $VP_{pre}$=3.5, S.E.=0.2). The mean force score increased at a slightly steeper rate to the mid-test for the PV sequence than the VP sequence ($PV_{mid}$=5.5, S.E.=0.2; $VP_{mid}$=5.2, S.E.=0.2). The mid-test to post-test trend was different in the two sequences. In the VP sequence, the mean score increased at the post-test ($VP_{post}$=5.4, S.E.=0.2). On the other hand, in the PV sequence, the mean score decreased at the post-test ($PV_{post}$=5.1, S.E.=0.2).

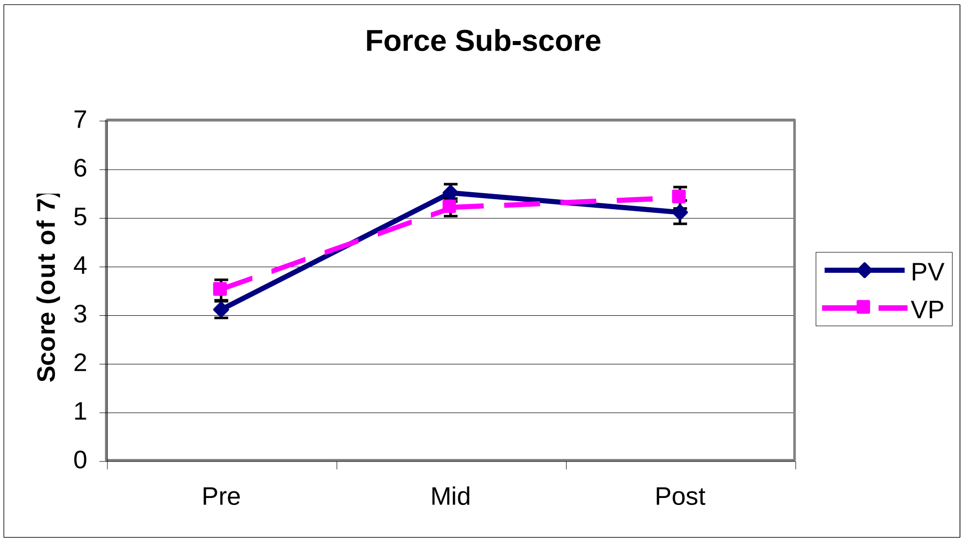


**Figure 6.10 Concepts of Physics Fall 2009 Test Scores: Force Sub-score.**

The main effect of test was significant, *F*(2, 196)=78.8, p<.001. Students' scores changed significantly from pre-test to mid-test, *F*(1, 196)=125.4, p<.001, r=0.62, and pre-test to post-test, *F*(1, 196)=112.4, p<.001, r=0.60. However, scores did not change significantly from mid-test to post-test, *F*(1, 196)=0.4, p=1.00, r=0.04. This indicates that students learned about force from their first pulley activity, but did not continue to learn about force in the second activity. The interaction of treatment with test was not significant, *F*(2, 196)=2.1, p=.122. This indicates that students' learning about force was supported equally by the physical and virtual manipulatives and the PV and VP sequences.

This result confirms the findings from the previous pulley studies. While one might expect the kinesthetic experience provided by the physical experiment to better support students' understanding of force, the physical and virtual manipulatives appear to offer equal support. However, the mean post-test score was less than 5.5 points out of seven possible points, which indicates students may need additional scaffolding to continue to develop their understanding of force in the context of pulleys.

### *6.3.3 Work/energy Sub-score*

Figure 6.11 below displays the mean pre-test, mid-test and post-test work/energy sub-scores for the PV and VP sequences. Students could earn up to a maximum of nine points on the work-energy sub-score, one point for each question related to work or potential energy. The mean pre-test work/energy score was similar for the two sequences ($PV_{pre}$=4.0, S.E.=0.2; $VP_{pre}$=4.1, S.E.=0.2). However, the mean work/energy score increased at the mid-test for the VP sequence, while it decreased for the PV sequence ($PV_{mid}$=3.6, S.E.=0.2; $VP_{mid}$=4.8, S.E.=0.3). At the post-test, the mean score increased for the PV sequence and decreased for the VP sequence ($PV_{post}$=3.9, S.E.=0.3; $VP_{pre}$=4.4, S.E.=0.3).

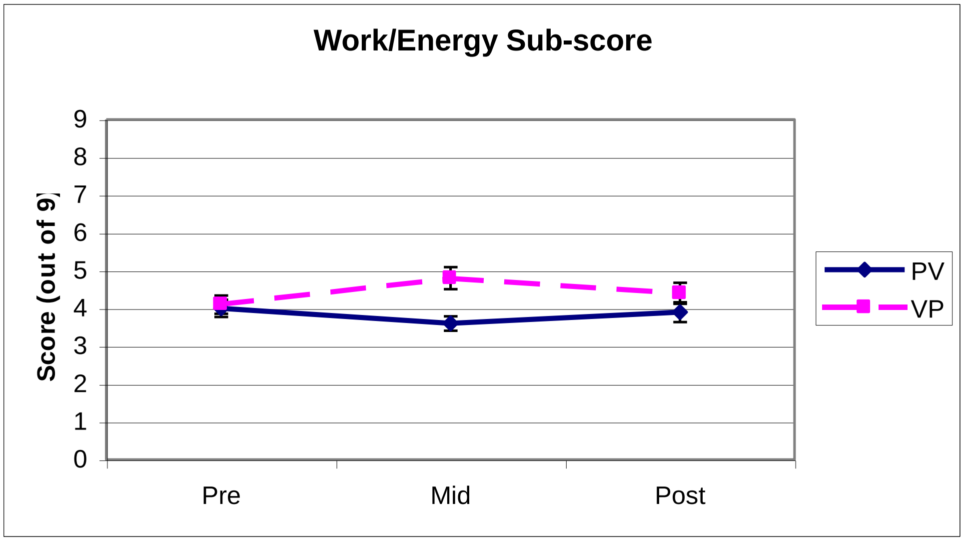


**Figure 6.11 Concepts of Physics Fall 2009 Test Scores: Work/Energy Sub-scores.**

The main effect of test was not significant, *F*(2, 196)=0.5, p=.582. This indicates that students did not learn about how work and potential energy relate to pulleys during the activities. The interaction of treatment with test was significant, *F*(2, 196)=4.4, p=.014. This indicates that students' scores changed differently in the two sequences. The interaction was significant from pre-test to mid-test, *F*(1, 196)=8.3, p=.004, r=0.20, and mid-test to post-test, *F*(1, 196)=4.0, p=.047, r=0.14. However, the interaction was not significant from pre-test to post-test, *F*(1, 196)=0.8, p=.377, r=0.06. Figure 6.11 shows the mean work/energy sub-score increased during the first activity in the VP sequence, but increased during the second activity in the PV sequence. Thus, it appears that the virtual activity provided better support for students' understanding of work and potential energy than did the physical activity. However, since the interaction was not significant from pre-test to post-test, both the PV and VP sequences appear to provide equal support. However, this support was weak, as students' scores did not increase significantly overall.

Unlike the students in the previous studies, students in the CoPF09 study do not appear to have learned about work from either the physical or virtual experiment. There are several possible reasons for this difference. While all of the participants in the pulley implementations were enrolled in introductory conceptual-based physics courses, the students in the CoPF09 study were all elementary education majors while the students in the PWS09 and PWF09 studies were from various non-science majors. So it is possible the CoPF09 participants had different background knowledge than the PWS09 and PWF09 participants. In addition, the CoPF09 pulley study was conducted during the first week of the semester while the other studies were conducted later in the semester. While pulleys are not specifically covered in either course, it is likely that the other material introduced in the courses better prepared students to learn about work and potential energy in the context of pulleys.

### *6.3.4 Mechanical Advantage Sub-score*

Figure 6.12 displays the mean pre-test, mid-test and post-test scores for the mechanical advantage sub-score for the PV and VP sequences. Students could earn up to a maximum of three points on the mechanical advantage sub-score, one point for each question related to mechanical advantage. The mean pre-test mechanical advantage scores were very similar for the two sequences ($PV_{pre}$=0.7, S.E.=0.1; $VP_{pre}$=0.8, S.E.=0.1). Scores for the two sequences were identical on the mid-test ($PV_{mid}$=1.4, S.E.=0.1; $VP_{mid}$=1.4, S.E.=0.1) and post-test ($PV_{post}$=1.5, S.E.=0.1; $VP_{pre}$=1.5, S.E.=0.1).

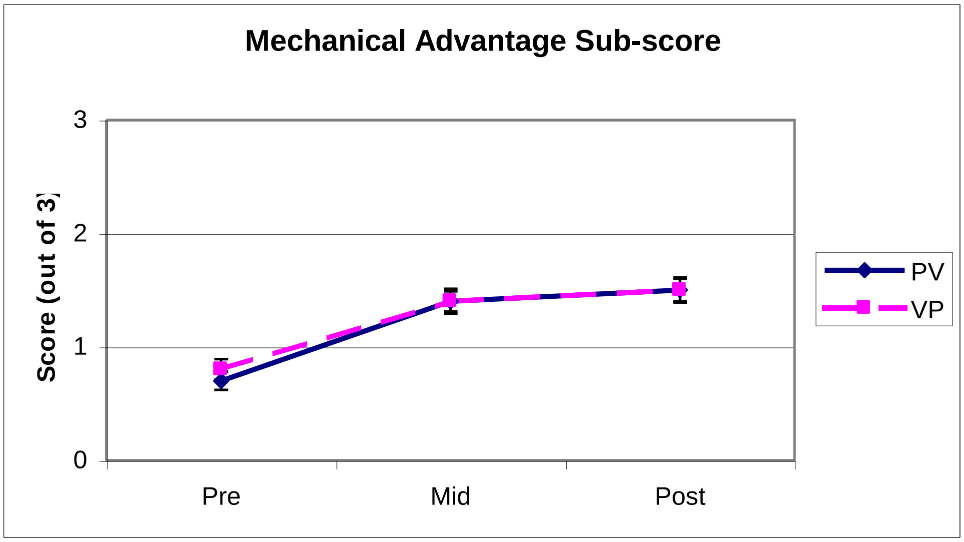


**Figure 6.12 Concepts of Physics Fall 2009 Test Scores: Mechanical Advantage Sub-score.**

The main effect of test was significant, *F*(2, 196)=47.6, p<.001. Students' scores increased significantly from pre-test to mid-test, *F*(1, 196)=62.4, p<.001, r=0.49, and from pre-test to post-test, *F*(1, 196)=79.2, <.001, r=0.54. However, scores did not change significantly from mid-test to post-test, *F*(1, 196)=1.2, p=.876, r=0.08. This indicates that students learned about mechanical advantage in their first activity, but did not continue to learn about mechanical advantage in their second activity. The interaction of treatment with test was not significant, *F*(2, 196)=0.1, p=.923. This indicates that students' scores did not change differently in the two sequences.

This result confirms the finding of the previous pulley studies that the physical and virtual manipulatives offer equal support for students' understanding of mechanical advantage. It seems that each manipulative could offer unique support for students' understanding of mechanical advantage. For example, the physical experiment allows students to physically feel the reduction in applied force needed to lift the load with pulley systems with higher mechanical advantage, while the simulation uses multiple representations (i.e. both numbers and graphs) to present the data about mechanical advantage. However, the mean mechanical advantage score increased by less than one point, which indicates students' may benefit from additional scaffolding to continue to develop their understanding of mechanical advantage.

### *6.3.5 Summary of Results*

Students in the CoPF09 study performed experiments with both physical and virtual manipulatives, either in the PV or VP sequence. This study design addresses several questions, such as whether the physical or virtual manipulative and PV or VP sequence offer better support for students' learning and whether performing the activity with the second type of manipulative continues to improve students' performance on the conceptual test. A summary of results of the mixed-ANOVA is shown in Table 6.3 below.

**Table 6.3 Summary of CoPF09 Test Analysis Statistics**

| **Score** | | **F-test** | | **Pre/Mid Contrast** | | **Mid/Post Contrast** | | **Pre/Post Contrast** | |
|---|---|---|---|---|---|---|---|---|---|
| | **Effect** | ***F*** | **p** | ***F*** | **p** | ***F*** | **p** | ***F*** | **p** |
| **Total** | **Test** | *F*(2, 196)= 56.8 | <.001 | *F*(1, 196)= 88.4 | <.001 | *F*(1, 196)= 0.1 | 1.00 | *F*(1, 196)= 82.8 | <.001 |
| | **Test* Treat** | *F*(2, 196)= 0.01 | .990 | | | | | | |
| **Force** | **Test** | *F*(2, 196)= 78.8 | <.001 | *F*(1, 196)= 125.4 | <.001 | *F*(1, 196)= 0.4 | 1.00 | *F*(1, 196)= 112.4 | <.001 |
| | **Test* Treat** | *F*(2, 196)= 2.1 | .122 | | | | | | |
| **WE** | **Test** | *F*(2, 196)= 0.5 | .582 | | | | | | |
| | **Test* Treat** | *F*(2, 196)= 4.4 | .014 | *F*(1, 196)= 8.3 | .004 | *F*(1, 196)= 4.0 | .047 | *F*(1, 196)= 0.8 | .377 |
| **MA** | **Test** | *F*(2, 196)= 47.6 | <.001 | *F*(1, 196)= 62.4 | <.001 | *F*(1, 196)= 1.2 | .876 | *F*(1, 196)= 79.2 | <.001 |
| | **Test* Treat** | *F*(2, 196)= 0.1 | .923 | | | | | | |

The results indicate that students learned only from the first experiment, whether it was physical or virtual, as the main effect ("test") mid-test/post-test contrast was not significant for total score or any of the concept sub-scores. Thus, it appears students did not continue to learn in the second activity. In addition, the physical and virtual manipulatives and PV and VP sequences appear to offer equal support for the total score and the force and mechanical advantage sub-scores, as the interaction was not significant for any of these scores. However, the virtual manipulative appears to offer better support for students' understanding of work and potential energy, as this interaction effect was significant and students' scores increased after completing the virtual activity. Still, the PV and VP sequences do not appear to support students' learning about work and potential energy differently, as the pre-test/post-test interaction contrast was not significant.

The CoPF09 study confirmed the findings from the previous pulley studies that the physical and virtual manipulatives offer equal support for students' learning about force and mechanical advantage. However, unlike the previous studies, students in the CoPF09 study did not appear to learn about work and potential energy from either the physical or virtual activity. This may due to a difference in background or the earlier timing in the semester of the CoPF09 study.

## 6.4 Trends in the Pulley Test Analysis

Students in the three pulley studies performed similar activities and took similar versions of the pulley conceptual test. Thus, it is useful to look for trends across the three studies. The main trend that emerges is that the virtual activity appears to help students perform better on the questions about work and potential energy than the physical activity. Students may more easily learn about work and energy in the frictionless environment provided by the simulation. The physical and virtual manipulatives appear to offer similar support for students' learning about force and mechanical advantage. In addition, both the PV and VP sequences seem to offer similar support for students overall learning as well as their understanding of the specific concepts.

Students appear to learn about force and mechanical advantage in only the first experiment, regardless of sequence. However, students' total scores and work/energy sub-scores improved during the second (virtual) activity in the PV sequence in the PWS09 and PWF09 studies. While the CoPF09 study did not exhibit this trend, this difference is likely due to the difference in timing of the post-test in this study. As explained more thoroughly in Chapter 4, all three tests were taken and both activities were completed in a two-hour time period in the PWS09 and PWF09 studies. However, the tests and activities were spread across five days in the CoPF09 study; thus, these students may not have retained as much information between the second activity and the post-test.

In addition, students' work-energy sub-scores did not improve in the CoPF09 study, while they did improve in the PWS09 and PWF09 studies. The participants in these studies were enrolled in different introductory physics courses.  Students in the CoPF09 study were enrolled in Concept of Physics, a course specifically for future elementary school teachers.  These students completed the pulley activity during the first week of the semester.  Students in the PWS09 and PWF09 studies were enrolled in The Physical World, a course for all non-science majors.  These students completed the pulley activity later in the semester.  Work and potential energy are typically difficult concepts for introductory physics students.  While neither the Concepts of Physics nor the Physical World lectures specifically covered the concept of pulleys, it is possible that the concepts that were covered in the first few weeks prepared students to learn about how work and energy relate to the pulley.

# CHAPTER 7 - Inclined Plane Worksheet Analysis

In this chapter, I discuss students' responses to the worksheet questions in the inclined plane studies. For each study, I describe the questions students were asked, the scientifically correct responses to those questions, the range of students' responses, and the frequency of those responses. Then I present the chi-square test of independence analysis on the responses provided by students who used physical or virtual equipment. Together, these results help address Research Question 1, specifically the questions:

- What do students learn from the physical activities, and what do they learn from the virtual activities?
- When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other?

## 7.1 Inclined Plane Study #1: Physical World Spring 2009 (PWS09)

In the PWS09 study, the inclined plane activity was broken into three sub-experiments. Students separately experimented with changing the length, height and surface (friction) of the inclined plane. Students used either physical or virtual manipulatives to perform the experiments. Due to time constraints, students completed only two of the three activities: either length and height, or length and friction. For a more in depth description of the study, see Section 4.3.1. It is important to note that the frictional force on the load is affected not only by the surface on the inclined plane, but also by changing the length or height as the normal force from the inclined plane on the load will be affected by a change in the angle of inclination.

After performing each sub-experiment, students responded to a set of open-ended analysis questions. In the following sections, I present the analysis of students' responses to these questions. In Section 7.1.1, I discuss each question and the types of student responses. In Section 7.1.2, I present the results of the chi-square test of independence used to compare the responses provided by students who used the physical or virtual manipulatives. In Section 7.1.3, I summarize the results of the worksheet data analysis.

### *7.1.1 Description of Students' Worksheet Responses*

In this study, the worksheet questions were associated with one of the three sub-experiments: length, height or friction. The questions asked after each experiment are discussed in the sections below. I present each question and the type of "scientifically correct" response we hoped students would provide after performing the experiments. Section 7.1.1.1 describes the Length Experiment Questions (LQ), Section 7.1.1.2 described the Height Experiment Questions (HQ), and Section 7.1.1.3 describes the Friction Experiment Questions (FQ).

#### *7.1.1.1 Length Experiment Questions*

LQ1 asked, "Based on your data, when you **increase the length** of the ramp, how does it affect the **effort force** needed to move the pool table up the ramp (for a given height)?" This question was asked to all students. The scientifically correct response is that less force is needed to move the pool table over a longer ramp than a shorter ramp (for the same height). A long ramp that is made to reach the same height as a short ramp will be less steep than the shorter ramp. Thus, less applied force is needed to keep the load from sliding down the ramp due to gravity.

Students' responses to LQ1 are shown in Figure 7.1 below. As shown, all students in all conditions successfully identified the relationship that the applied force needed to lift the load decreases as the length of the inclined plane increases.

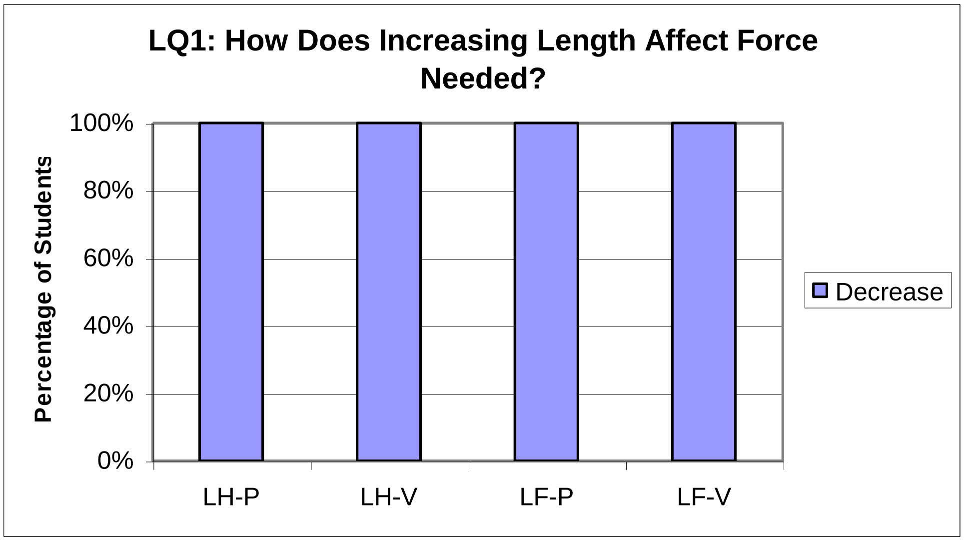


**Figure 7.1 PWS09 Inclined plane worksheet responses: Length Question 1.**

LQ2 asked, "Based on your data, when you **increase the length** of the ramp, how does it affect the **work** needed to move the pool table up the ramp (for a given height)?" This question was asked to all students. For a frictionless ramp, the work needed to lift the load does not depend on length; the work needed would be equal to the change in the load's potential energy, which depends only on height and weight. However, in the physical experiment, friction on the ramp's surface would require more force to move the load and create more work needed.

Students' responses varied across the four conditions, as shown in Figure 7.2 below. Students who used the computer simulation most commonly (more than 50%) responded that the work stays the same when the length of the ramp increases. Students answered this question immediately after performing the length experiment, which is completely frictionless in the simulation. Students who performed the length and height virtual activities more frequently responded that the work is similar for different lengths of ramps (30%) than students who performed the length and friction virtual experiments (7%). On the other hand, students who used the physical equipment most commonly (more than 65%) responded that work increases when the length of the ramp increases. This response mirrors the behavior students observed in the physical experiment due to frictional effects. Some students who performed the length/height physical experiments (17%) and length/friction virtual experiments (5%) stated the work decreases when the length of the ramp increases.

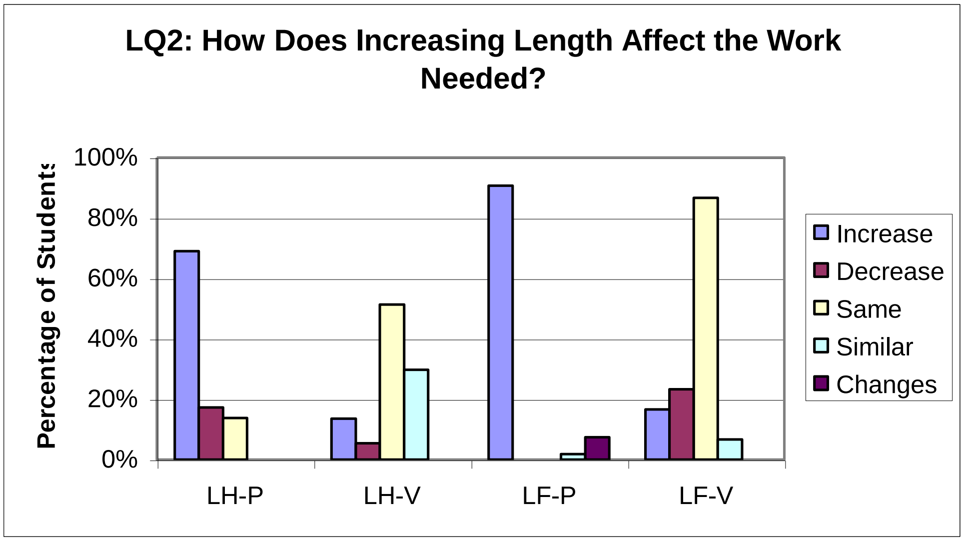


**Figure 7.2 PWS09 Inclined plane worksheet responses: Length Question 2.**

LQ3 asked, "Based on your data, when you **increase the length** of the ramp, how does it affect the **Ideal Mechanical Advantage** (for a given height)?" This question was asked to all students. Mechanical advantage is a measure of how much the inclined plane reduces the applied force needed to lift the load. Ideal mechanical advantage is calculated by dividing the length of the inclined plane by its height. Therefore, a longer ramp will have a higher ideal mechanical advantage. This makes physical sense because it is easier to pull the load up a less steep ramp.

As shown in Figure 7.3 below, the vast majority of students (more than 90%) were able to correctly identify the trend that increasing length decreased mechanical advantage. A few students provided responses that could not be interpreted (i.e., simply wrote “Yes.”)

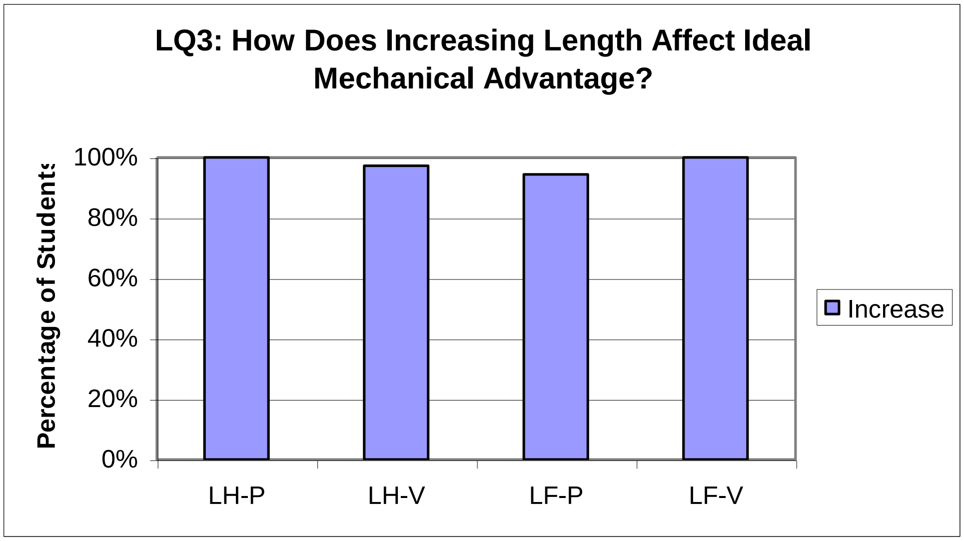


**Figure 7.3 PWS09 Inclined plane worksheet responses: Length Question 3.**

LQ4 asked, “Based on your data, when you **increase the length** of the ramp, how does it affect the **Actual Mechanical Advantage** (for a given height)?” This question was asked to all students. Actual mechanical advantage is calculated by dividing the weight of the object by the force needed to lift the object. Since a longer ramp requires less force to lift the load, it will have a higher actual mechanical advantage. Because actual mechanical advantage is based on the applied force, it accounts for the effects of friction, unlike ideal mechanical advantage.

As shown in Figure 7.4 below, the majority of students (more than 80%) were able to correctly identify the relationship that actual mechanical advantage increased when the length of the ramp was increased. A few students stated that the actual mechanical advantage decreased when the ramp length was increased; this response was most common for students who had completed the length and height physical experiments (17%).

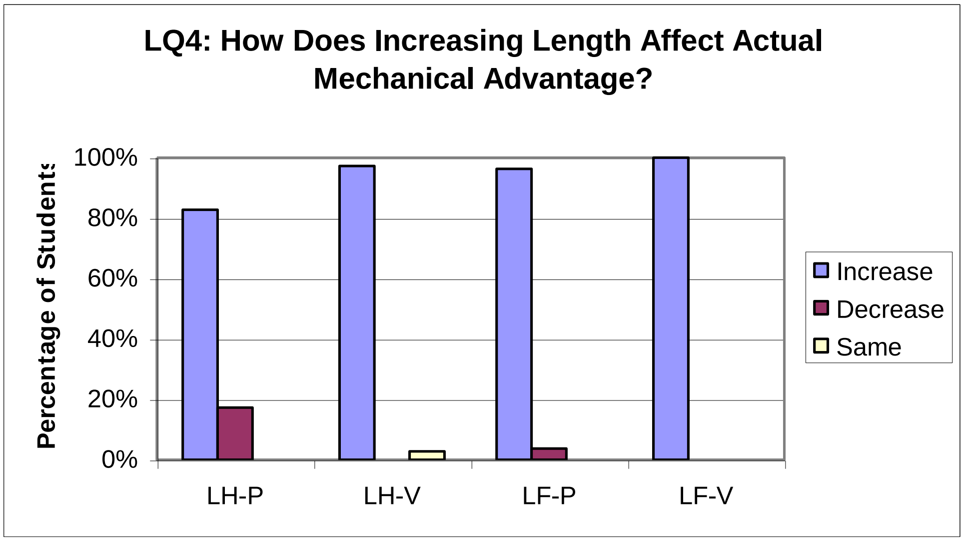


**Figure 7.4 PWS09 Inclined plane worksheet responses: Length Question 4.**

LQ5 asked, “What do you think is the **effort force** needed to lift the pool table into the van without the use of a ramp?” This question was asked only of students who performed the virtual activity. Without a ramp, the applied force would need to balance the force of gravity on the object. A minimum applied force equal to the weight of the object would lift the load at constant velocity; a larger applied force would cause the load to accelerate.

Students provided a variety of answers to LQ5, as shown in Figure 7.5 below. While the two groups of students shown performed different second activities (height or friction), LQ5 was answered immediately after the first experiment (length). Students most commonly (about 30% in the length/friction group and about 60% in the length/height group) responded that more applied force would be needed to lift the load without the ramp than with the ramp. Some students (about 30%) specified that the necessary applied force would be equivalent to the weight of the load. Other students responded that the force must be at least equal to (about 10% in the length/height group and about 20% in the length/friction group) or more than the load (about 20% in the length/friction group only). This question demonstrates that students’ intuitions about force are useful, as these students did not have the opportunity to explore lifting the load without a ramp but were able to answer the question correctly.

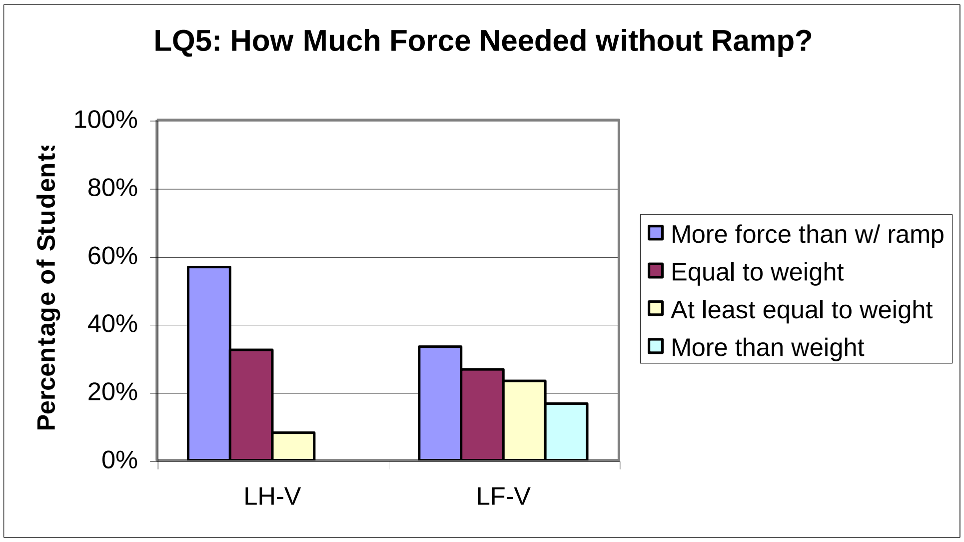


**Figure 7.5 PWS09 Inclined plane worksheet responses: Length Question 5.**

LQ6 asked, "What do you think is the **work** needed to lift the pool table into the van without the use of a ramp?" This question was asked only of students who performed the virtual activity. Work is equal to the applied force times the distance over which the force is applied. The minimum work is equal to weight of the object times the height of the ramp. If more work is put into the system, it will be transferred to changing the kinetic energy of the load.

Again, students responded to LQ6 immediately after performing the length experiment, so both groups of students shown in Figure 7.6 below had the same experiences before responding to this question. However, the distribution of responses differed between the two groups. Many students recognized that the work would be the same with and without a ramp (about 60% in length/height group and 30% in length/friction group). Other students responded with the equation to calculate the work needed (about 10% in length/height group and 3% in length/friction group). Some students mistakenly predicted that the work would be greater (5% in length/height group and about 20% in length/friction group) or less (5% in length/height group and about 10% in length/friction group) without the ramp than with the ramp. Students also provided many additional answers, such as equating work with force. It is surprising that the distribution of responses differed as the two groups of students had the same learning experiences prior to answering LQ5 and LQ6.

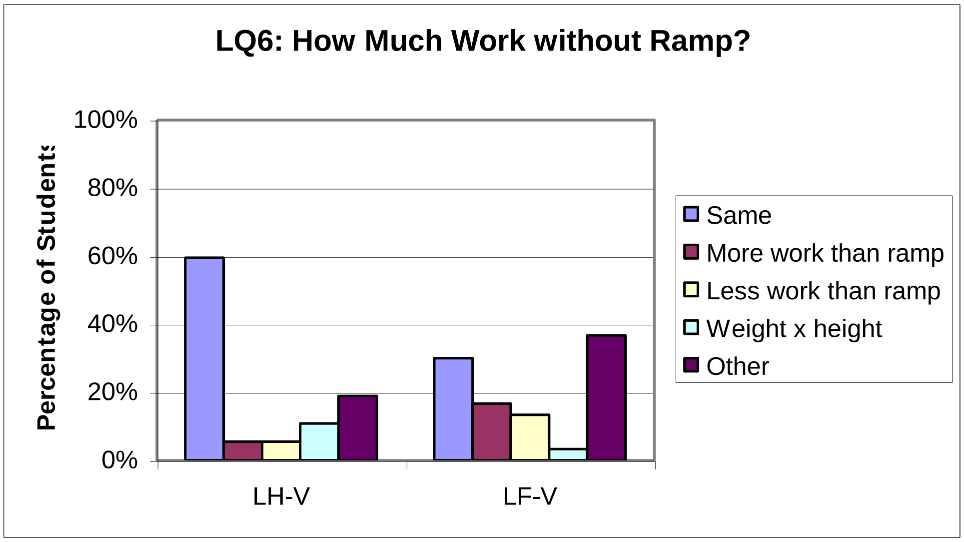


**Figure 7.6 PWS09 Inclined plane worksheet responses: Length Question 6.**

### *7.1.1.2 Height Experiment Questions*

HQ1 asked, “Based on your data, when you **increase the height** of the ramp, how does it affect the **effort force** needed to pull the block up the ramp (for the same length)?” This question was asked to all students who completed the height experiment. The scientifically correct response is that a higher ramp will require more applied force to lift the load. When a constant length ramp is made to reach a taller height, the slope of the ramp becomes steeper. More force is needed to keep the load from sliding back down the board due to gravity.

As shown in Figure 7.7 below, all students who completed the height activity were able to correctly identify the relationship that increasing the ramp’s height increases the force needed to lift the load.

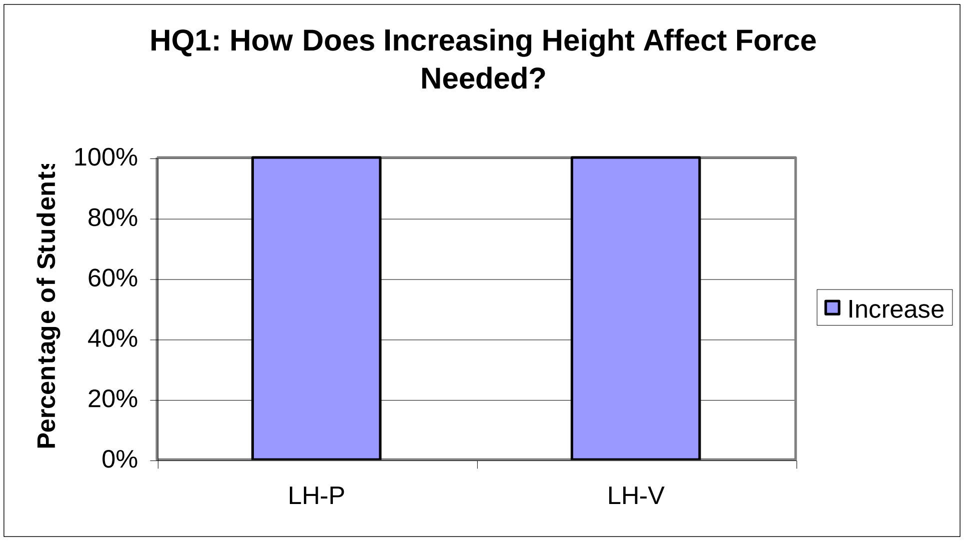


**Figure 7.7 PWS09 Inclined plane worksheet responses: Height Question 1.**

HQ2 asked, "Based on your data, when you **increase the height** of the ramp, how does it affect the **work** needed to pull the block up the ramp (for the same length)?" This question was asked to all students who completed the height experiment. The scientifically correct response is that more work is needed to lift the load to the top of a higher ramp. In moving to the top of a higher ramp, the load will undergo a greater change in potential energy than in moving to a shorter height. More work must be used to create the greater change in potential energy.

As shown in Figure 7.8 below, the majority of students (more than 80%) correctly identified the relationship that increasing the ramp's height increases the work needed to lift the load. Several students (about 20%) who used the physical equipment stated that increasing the height decreases the work. These students were all in the same group, and seem to have misinterpreted the question. Their data tables showed that the correct pattern that the work increased when the height increased (e.g. from 122 J for a height of 6 cm to 152.5 J for a height of 22 cm). However, the students responded that the work decreased because the force decreased. It seems likely these students were thinking about length rather than height.

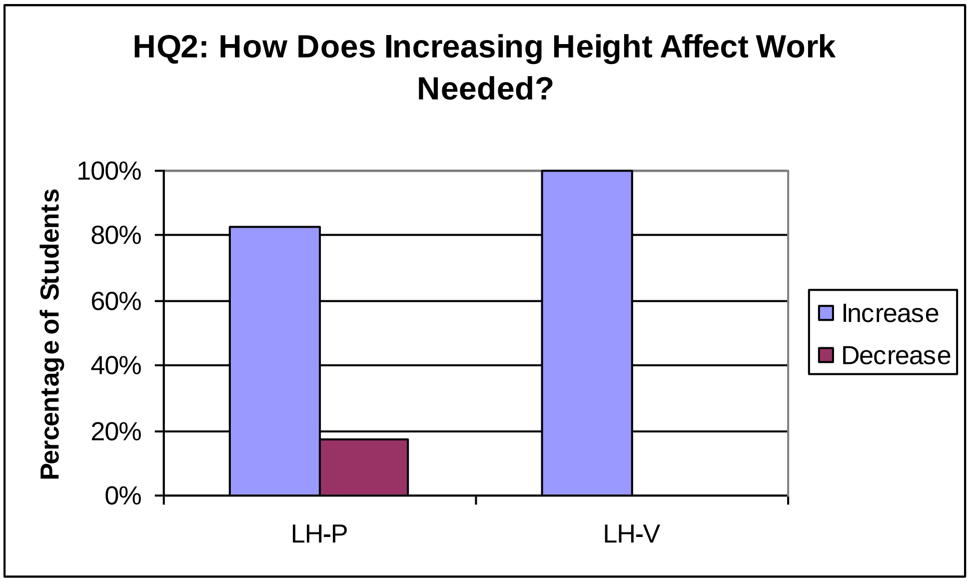


**Figure 7.8 PWS09 Inclined plane worksheet responses: Height Question 2.**

HQ3 asked, “Based on your data, how does **work** compare to **potential energy**?” This question was asked to all students who completed the height experiment. For a frictionless ramp, the work used to lift the load would be equal to the change in its potential energy. In the physical experiment, the work will be greater than the change in potential energy because some energy is transferred to heat due to friction.

Students’ responses varied based on whether they had used the physical equipment or computer simulation to perform the height experiment, as shown in Figure 7.9 below. The majority (about 80%) of students who had performed the virtual experiment responded that work was equal to potential energy. Students were able to observe this relationship due to the frictionless environment of the height simulation. Students who completed the physical experiment did not provide this response. Rather, these students more commonly stated that when there was more work, there was also more potential energy (about 60%) or that the work was greater than potential energy (about 30%). In the physical experiment, students did observe that the work needed to lift the load was greater than the load’s change in potential energy due to frictional effects. Our goal is for the students to understand how the relationship under ideal conditions (work is equal to change in potential energy) relates to the relationship under “real world” conditions. It appears students may need additional support to understand this connection. Additional questions were added to the worksheet in the following study to better explore students' understanding of how the relationship between work and potential energy depends on friction.

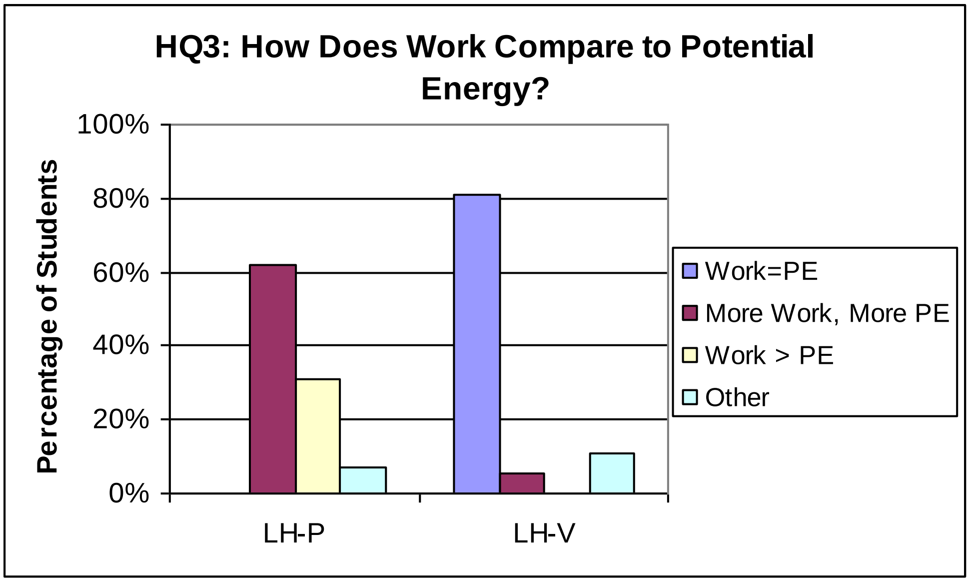


**Figure 7.9 PWS09 Inclined plane worksheet responses: Height Question 3.**

### *7.1.1.3 Friction Experiment Questions*

FQ1 asked, "Based on your data, when you **increase friction**, how does it affect the **effort force** needed to pull the block up the ramp?" This question was asked to all students who completed the friction experiment. The scientifically correct response is that more force is needed to lift the load up a ramp with more friction. Friction opposes the direction of motion, so more force is required to overcome friction.

As shown in Figure 7.10 below, the vast majority of students (nearly 100%) were able to correctly identify the relationship that increasing friction increases the force needed to lift the load. One student in the length/friction physical group did not respond.

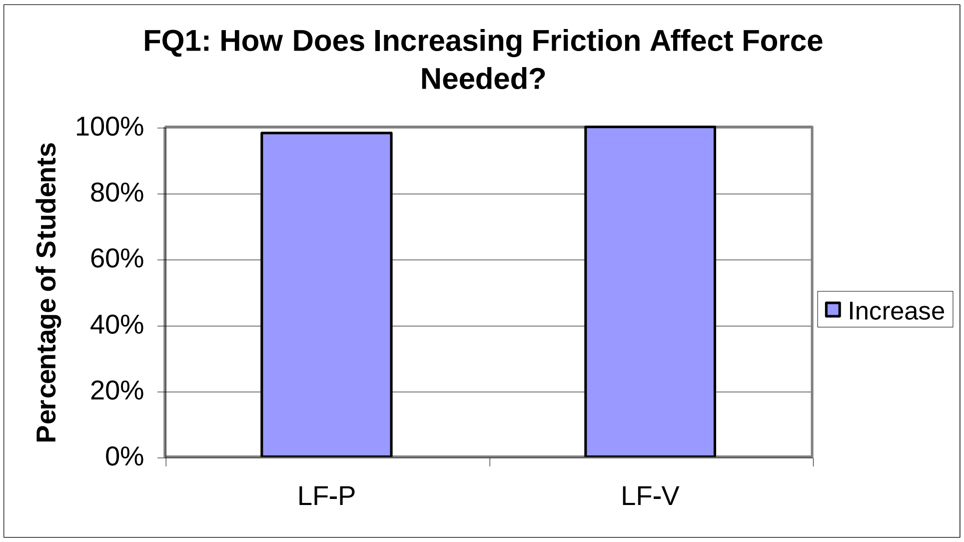


**Figure 7.10 PWS09 Inclined plane worksheet responses: Friction Question 1.**

FQ2 asked, “Based on your data, when you **increase friction**, how does it affect the **work** needed to pull the block up the ramp?” This question was asked to all students who completed the friction experiment. The scientifically correct response is that a ramp with more friction will require more work to lift the load since more force is required to overcome friction.

As shown in Figure 7.11, the vast majority (more than 90%) of students correctly identified the relationship that increasing friction increased the work required to lift the load using the inclined plane. Four students in the length/friction physical group did not respond.

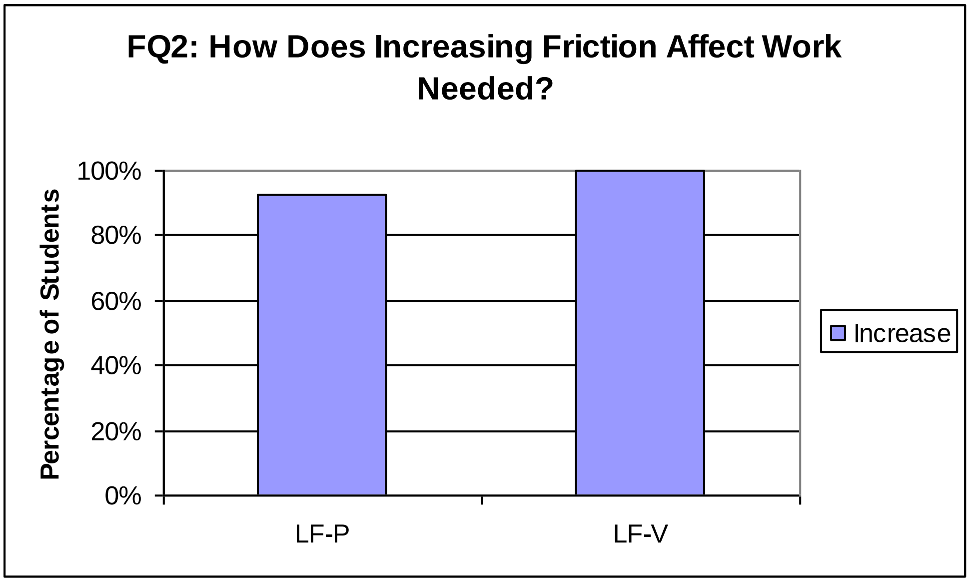


**Figure 7.11 PWS09 Inclined plane worksheet responses: Friction Question 2.**

FQ3 asked, “Based on your data, when you **increase friction**, how does it affect **Ideal mechanical advantage**?” This question was asked to all students who completed the friction experiment. As stated above, ideal mechanical advantage is calculated by dividing the length of the inclined plane by its height. Thus, the ideal mechanical advantage is not affected by friction. This is the difference between ideal and actual mechanical advantage.

As shown in Figure 7.12, the vast majority (more than 85%) of students correctly responded that friction does not affect ideal mechanical advantage. Seven students in the length/friction physical group did not respond to this question.

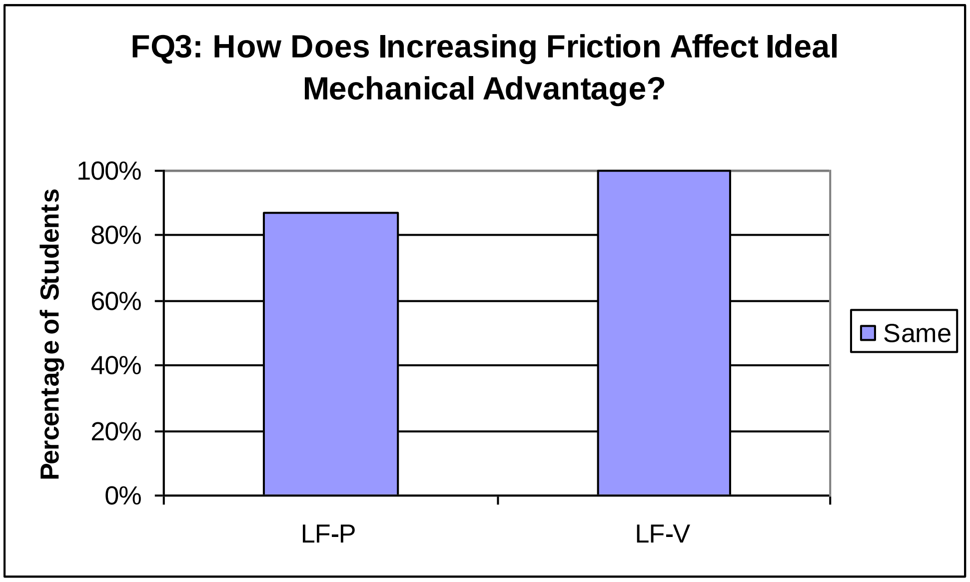


**Figure 7.12 PWS09 Inclined plane worksheet responses: Friction Question 3.**

FQ4 asked, "Based on your data, when you **increase friction**, how does it affect **Actual mechanical advantage**?" This question was asked to all students who completed the friction experiment. As stated above, actual mechanical advantage is calculated by dividing the object's weight by the applied force needed to lift it up the ramp. Because higher friction requires more force to lift the object, increasing friction decreases an inclined plane's actual mechanical advantage.

As shown in Figure 7.13 below, the majority (more than 80%) of students correctly identified the relationship that increasing friction decreases the inclined plane's actual mechanical advantage. In the length/friction physical group, very few students (4%) gave different answers and seven students did not respond.

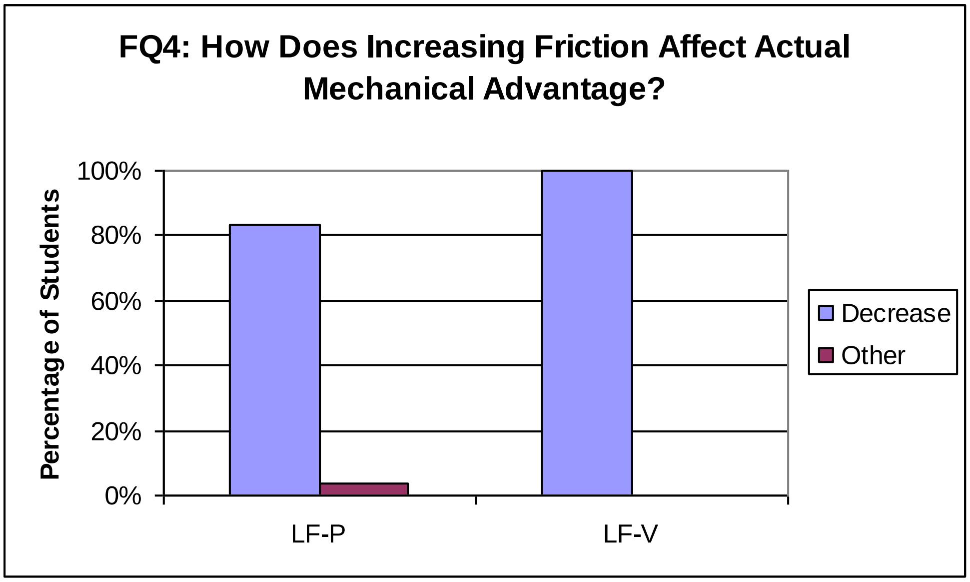


**Figure 7.13 PWS09 Inclined plane worksheet responses: Friction Question 4.**

FQ5 asked, “Based on your data, how does the relationship between **Ideal MA** and **Actual MA** depend on friction?” This question was asked to all students who completed the friction experiment. The difference between ideal and actual mechanical advantage is that actual accounts for friction while ideal does not. Thus, ideal mechanical advantage yields the highest possible mechanical advantage for a given inclined plane. The actual mechanical advantage gets closer in value to the ideal as friction is reduced.

As shown in Figure 7.14 below, students provided a variety of responses to FQ5. Many of these responses are scientifically correct, but address the question in different ways. For example, students most commonly (about 45%) responded that ideal mechanical advantage does not depend on friction, while actual mechanical advantage does (i.e. “Friction only affects the actual MA, but doesn't for ideal.”) This information is correct, but does not discuss the relationship in the way the question intended. Other common responses were that friction increases the difference between ideal and actual mechanical advantage (i.e. “The more friction the greater the difference is between the ideal MA and Actual MA”; provided by 20% of students in physical condition and about 40% in virtual condition) and that ideal mechanical advantage is greater than actual mechanical advantage (i.e. “The relationship between the ideal and the actual is never the same, but the actual is always less”; provided by about 10% of students in physical condition and 20% in virtual condition). These responses more thoroughly discuss the relationship between the ideal and actual mechanical advantage. A few students (9%) who had performed the physical experiment stated that increasing friction decreases the difference between ideal and actual mechanical advantage.

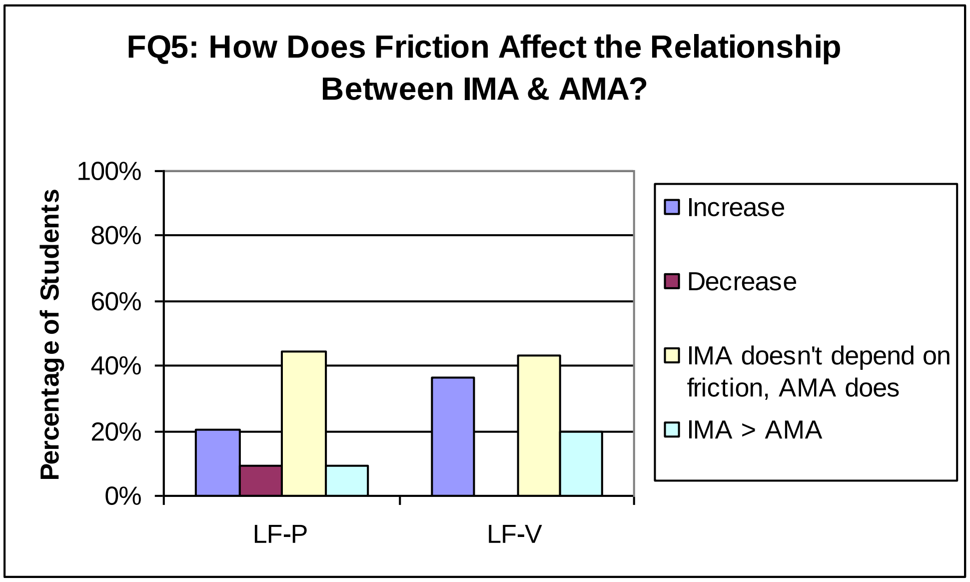


**Figure 7.14 PWS09 Inclined plane worksheet responses: Friction Question 5.**

FQ6 asked, “Predict what would be the relationship between **Ideal MA** and **Actual MA** if the board were **frictionless**?” This question was asked only to students who completed the friction experiment with physical equipment. As stated above, ideal and actual mechanical advantage become closer in value as friction is reduced. For a completely frictionless ramp, the two would be equal.

Students appear to be able to predict the behavior of mechanical advantage in the frictionless case based on their experiences with the physical experiment. As shown in Figure 7.15 below, the most common response (provided by more than 40% of students) was that actual and ideal mechanical advantage would be equal for a frictionless ramp. The remaining students most commonly (about 40%) responded that ideal and actual mechanical advantage get closer as friction decreases. These students successfully described the physical behavior of the system, but did not generalize this behavior to the ideal case.

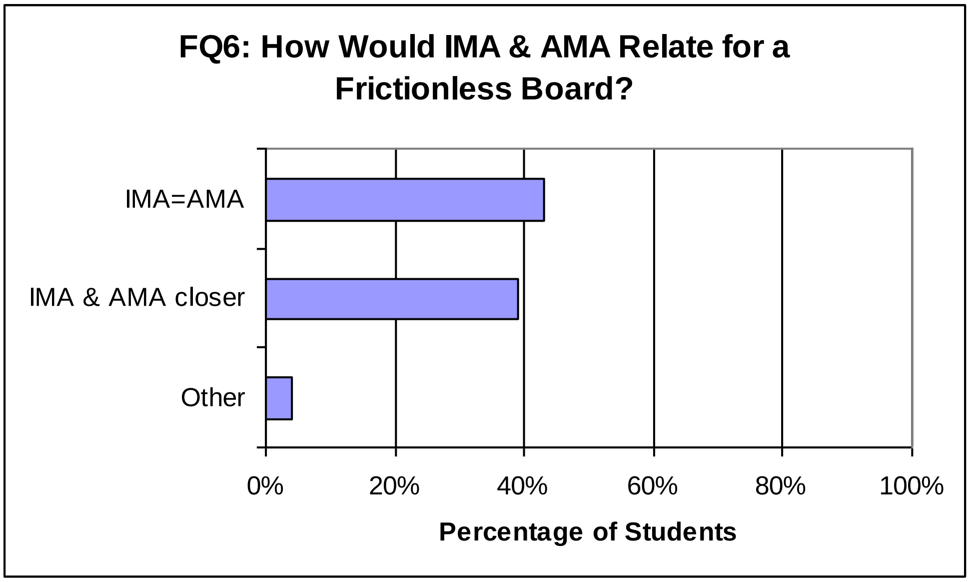


**Figure 7.15 PWS09 Inclined plane worksheet responses: Friction Question 6.**

FQ7 asked, "Based on your data, how does the relationship between **work** and **potential energy** depend on friction?" This question was asked only to students who completed the friction experiment with physical equipment. The minimum work needed to lift the load is equal to the change in the load's potential energy. The presence of friction causes the work needed to increase, as more force is required to overcome friction. The work and potential energy get closer as friction is reduced.

As shown in Figure 7.16 below, students provided a variety of answers to describe the relationship between work and potential energy. The most common response (provided by about 55% of students) was that friction affects work but does not affect potential energy. These students correctly described how friction affects work and potential energy, but failed to describe how work and potential energy compare. The next common response (provided by about 20% of students) was that the difference between work and potential energy increases when friction increases; this is the response we hoped students would provide after performing the experiment. Other students responded only about work (4%) or provided alternate answers (9%). As discussed below, it is possible that the simulation prompted students to compare quantities, such as work and potential energy, and that students need additional support to do this is in the physical experiment.

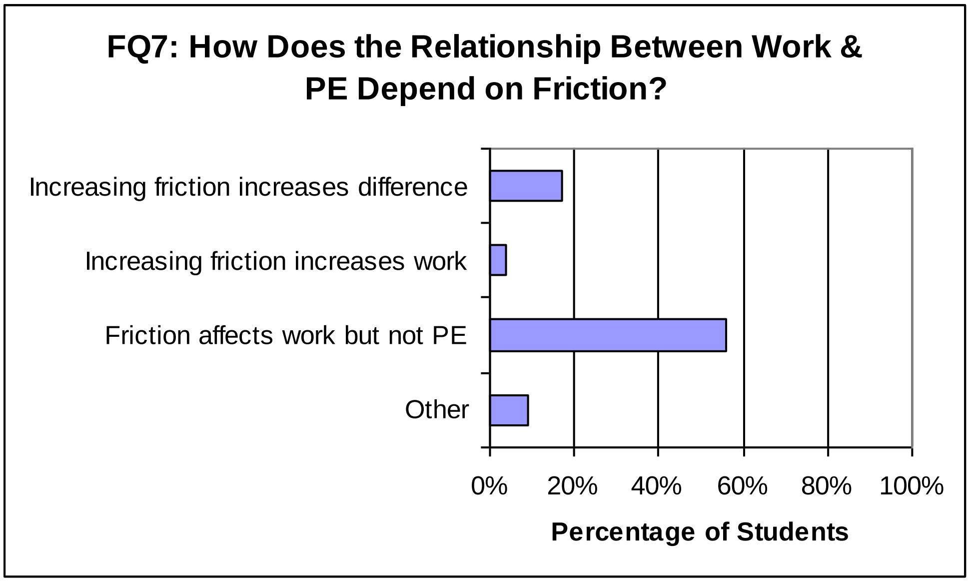


**Figure 7.16 PWS09 Inclined plane worksheet responses: Friction Question 7.**

FQ8 asked, "Predict what would be the relationship between **work** and **potential energy** if the board were **frictionless**?" This question was asked only to students who completed the friction experiment with physical equipment. As stated above, the work and potential energy get closer as friction is reduced. For a completely frictionless ramp, the two would be equal.

Figure 7.17 displays students' responses to FQ8. Again, students provided two main types of responses. Some students (33%) discussed the relationship between work and potential energy as intended, by stating that work and potential energy get closer. Other students (another 33%) discussed work and potential energy separately, by stating that friction does not affect potential energy but less friction leads to less work. Students also appear to have difficulty generalizing to the frictionless case from the physical experiment. A few students (11%) indicated that work would be less than potential energy without friction. No students responded that work and potential energy would be equal.

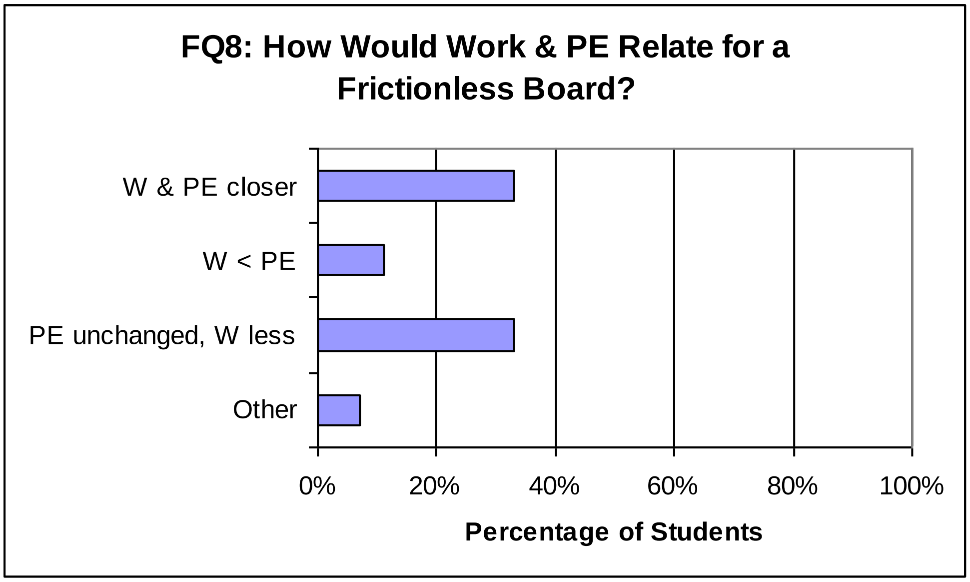


**Figure 7.17 PWS09 Inclined plane worksheet responses: Friction Question 8.**

### *7.1.2 Chi-square Statistical Analysis*

Students' worksheet question responses were compared using a chi-square test for independence. Because I am interested in how physical and virtual manipulatives support students' learning, only questions answered during both the physical and virtual experiments were analyzed. A significant chi-square test result indicates that the responses likely came from two different populations. If the number of students expected to give a certain response in any treatment was less than five, Fisher's exact test was used. The results of the analysis for these questions are shown in Table 7.1 below; Fisher's exact test was used for each test. On several questions of this set, all students provided the same answer, so the chi-square test was not needed. These questions are indicated by "N/A" in the chi-square statistic column, and their significance values and effect size are left blank. When the chi-square test was significant, the adjusted residuals were examined to identify which cells exhibited independence; adjusted residuals greater than 1.96 were taken to be significant (Haberman, 1973).

### Table 7.1 PWS09 Inclined Plane Worksheet Analysis Statistics

| **Q** | **Concept** | **Parameter** | **$\chi^2$ *** | **p**** | **V***** |
|---|---|---|---|---|---|
| LQ1 | Force | Length | N/A | | |
| LQ2 | Work | Length | $\chi^2$(12, N=158) =125.5 | **<.001** | .89 |
| LQ3 | Ideal Mechanical Advantage | Length | N/A | | |
| LQ4 | Actual Mechanical Advantage | Length | $\chi^2$(6, N=150) =12.3 | **.007** | .29 |
| HQ1 | Force | Height | N/A | | |
| HQ2 | Work | Height | $\chi^2$(1, N=66) =6.9 | **.013** | .32 |
| HQ3 | Work/Potential Energy | Height | $\chi^2$(3, N=65) =61.3 | **<.001** | .97 |
| FQ1 | Force | Surface | N/A | | |
| FQ2 | Work | Surface | N/A | | |
| FQ3 | Ideal Mechanical Advantage | Surface | N/A | | |
| FQ4 | Actual Mechanical Advantage | Surface | $\chi^2$(1, N=77) =1.3 | .518 | .13 |
| FQ5 | Ideal/Actual Mechanical Advantage | Surface | $\chi^2$(3, N=75) =5.6 | .143 | .27 |

*The format is $\chi^2$(degrees of freedom, N) =chi-square statistics
**Significance value
***Effect size

Only four questions exhibited statistical significance. The significantly different responses for each question are described below.

LQ2 asked students to describe how changing the length of an inclined plane (while keeping the height constant) would affect work. Students who used the computer simulation to complete the length experiment were more likely to say length didn’t affect work than were students who used the physical equipment. Students in the Length/Height Virtual group were more likely than students in the Length/Friction Physical group to say work mostly stayed the same when length was changed. On the other hand, students who used the physical equipment were more likely to say work increased when the length increased than students who used the simulation. Students in the Length/Friction Virtual group were more likely to respond that increasing the length of the plane decreased the work needed, while students in the Length/Friction physical group were less likely to provide this response. Students in the Length/Friction Virtual group were more likely to respond in general that increasing the length of the inclined plane changed the work needed. This analysis demonstrates that students who used the physical equipment interpreted the change in work due to friction when the length was changed as significant and were less likely to state the idealized relationship that the length of the ramp does not affect work than were students who performed the virtual activity.  This result is not surprising as students who used the simulation were presented with idealized data, while students who used the physical equipment gathered “real-world” data that included frictional effects and measurement errors.

LQ4 asked students to describe how increasing the length of the inclined plane affected actual mechanical advantage.  Students who performed the Length/Height Physical activities were less likely to identify the correct relationship that increasing length increased actual mechanical advantage than students who performed the other activities.  It is possible that students who had changed the height of the ramp confused the effect of changing length and height.  Returning to Figure 7.4 above, students who performed the Length/Height Physical activity were more likely to state that increasing the length of the ramp decreased the actual mechanical advantage than were students in the other groups.  Increasing the height would in fact decrease the mechanical advantage, so one possibility is that these students were confusing the effect of changing the length and height.

HQ2 asked students to describe how increasing the height of the inclined plane affected the work needed to lift the load.  This question was only answered by students who completed the height activity.  Among these students, those who used the physical equipment were more likely to state that increasing height decreased work and less likely to state that increasing height increased work than those who used the simulation.  As discussed above, the data tables of the students who made this mistake did not display this trend.  Thus, it seems likely that students were confusing the effects of changing length and height.

HQ3 asked students to compare work and potential energy.  Like HQ2, this question was only answered by students who completed the height activity.  Among those students, those who performed the virtual experiment were more likely to respond that work equals potential energy than those who performed the physical experiment.  The students who used the physical experiment were instead more likely to respond that more work meant more potential energy or that work was greater than potential energy.  It appears that the simulation better supports students to make comparisons between concepts, like work and potential energy, than does the physical experiment.  It is possible that the simulation provides more support for dynamic transfer, or the creation of new conceptions, than does the physical equipment. This is further explored in Chapter 9.

### *7.2.3 Summary*

In the PWS09 study, students used either physical or virtual manipulatives to perform experiments about either length and height or length and friction in the context of inclined planes. This analysis focuses on questions asked in two different manners. Some questions were asked to both students who had used the physical equipment and to students who had used the computer simulation. These questions allow for comparison of what trends students drew from the physical and virtual experiments. Other questions were asked as prediction questions to the students whose manipulative did not allow for a certain type of experiment. Specifically, students who performed the length experiment with the simulation were not able to explore a "vertical lift", or lifting the load without using an inclined plane, as the simulation did not allow students to make the length and height of the ramp equal, nor could they remove the ramp completely. Similarly, students who performed the friction experiment with the physical equipment were not able to explore a frictionless ramp. These questions allow for exploration of students' ability to extend their ideas beyond the experiment they performed. The findings of these two types of questions, physical/virtual comparisons and predictions, are discussed separately below.

The physical/virtual comparison questions focused on several aspects of the inclined plane (length, height and surface) and several physics concepts (force, work, mechanical advantage and potential energy). Students who had used the physical or virtual manipulatives provided similar answers to many of these questions. Specifically, the answers given by both groups were similar for questions about force and mechanical advantage in connection with length and height and for all concepts in connection with friction. This suggests that the physical and virtual manipulatives equally support students learning about the surface of the inclined plane, force and mechanical advantage. It is perhaps surprising that the physical and virtual manipulatives provided equal support for students' understanding of force, since the physical equipment provides students with the kinesthetic experience of feeling the force applied while the simulation does not. On the other hand, it is not surprising that mechanical advantage is equally supported by both manipulatives, as it is an abstract concept with close ties to force; thus, each manipulative seems to have specific benefits for students' learning about mechanical advantage.

Differences emerged on questions about work when students were asked to consider changing the length or height. It makes sense that students who use the physical or virtual manipulatives talked about work differently because the ramps in the simulation were frictionless for the length experiment and the physical ramps cannot be made frictionless. Thus, students who used the physical manipulatives observed that increasing the length of the inclined plane resulted in an increase in work. However, some students who used the physical equipment stated that the work needed to lift the load using the inclined plane decreased when the height of the ramp was increased. This disagrees with what the students should have observed in the physical height experiment. In addition, students who used the physical or virtual manipulatives provided different types of responses when asked to compare work and potential energy. Students who used the simulation were more likely to compare work and potential energy ("work equals potential energy"), while students who used the physical equipment were more likely to talk about work and potential energy separately ("more work, more potential energy"). This suggests the simulation may be better at helping students see the connections between work and potential energy.

Students who used the simulation were asked to make predictions about the force and work needed to lift a load without using the inclined plane. This was a prediction for these students because they were not able to investigate a "vertical lift" in the simulation. Students were generally successful at discussing the necessary applied force, stating that it would be more than with the ramp or equal to the load's weight. However, students had more difficulty predicting the work required. Many students recognized that the work would be the same with or without the ramp, but many students struggled, stating the work would be more or less without the ramp. This indicates that even the students who used the virtual manipulative did not have a sufficient understanding of work after performing the length experiment.

Students who used the physical equipment were asked to make predictions about the ideal, frictionless case because they were not able to investigate a frictionless ramp in the physical experiment. Many students successfully predicted that ideal mechanical advantage and actual mechanical advantage would be equal in a frictionless environment. It is possible students spent more time thinking about mechanical advantage because it was an unfamiliar concept. On the other hand, no students predicted that work and potential energy would be equal in a frictionless environment.  This suggests students need additional support to reason about the ideal case from the physical experiment.

Overall, the physical and virtual experiments seem to have provided equal support for students' learning about force and mechanical advantage as assessed by the worksheet questions. Students who performed the physical experiment had more difficulty understanding work in an ideal context than students who performed the virtual experiment.

## 7.2 Inclined Plane Study #2: PWF09

In the PWF09 study, students performed both activities with both physical and virtual manipulatives, but in different orders.  Some students completed the physical activity followed by the virtual activity (PV sequence), and others completed the virtual activity followed by the physical activity (VP sequence).  In each activity, students performed trials that varied the length, height and surface of the inclined plane.  For a more complete description of the study, see Section 4.3.2.

After completing each activity (physical and virtual), the students answered a set of analysis questions.  The questions were broken down by physics concept, and this format is followed in the discussion below.  In Section 7.2.1, I discuss the types of responses students provided.  In Section 7.2.2, I present the results of the chi-square test for independence performed on the responses provided by students in the PV and VP sequences.  In Section 7.2.3, I summarize the findings of the worksheet data analysis.

### *7.2.1 Description of Students' Worksheet Responses*

#### *7.2.1.1 Worksheet Question 1: Force*

WQ1 asked the students how the force needed to move the load would be affected if changes were made to the length, height and surface of the ramp.  The distributions of response categories are shown in Figures 7.18, 7.21, and 7.22 below.

The first part of WQ1 asked, "How does the *effort force* needed to move the load change if the *length* of the ramp **increases**?"  The scientifically correct answer is that a longer ramp requires less force to move the load.  Because a longer ramp is less steep, less force is needed to keep the object from sliding down the ramp due to the force of gravity.

As shown in Figure 7.18, the majority of students responded that as the length of the ramp increased, the force needed to move the load would decrease. Some students responded that the force would increase or that the force would stay the same if the length of the ramp were increased. However, the prevalence of these responses differed by activity and activity sequence. In the PV sequence, while about 20% of students responded that the force would not change with the length in the physical activity, nearly all students responded that the force would decrease if the length were increased in the virtual activity. Overall, a smaller percentage of students in the VP sequence (78% after virtual experiment, 49% after physical experiment) than the PV sequence (78% after physical experiment, 96% after virtual experiment) responded that the force would decrease if the length were increased. The percentage of students providing this response decreased from the virtual activity to the physical activity. It is unclear how the activities affected students' understanding of how ramp length affects the force needed. Overall, students in the PV sequence more frequently provided the correct response, but the prevalence of the correct response increased when they performed the virtual activity. On the other hand, the percentage of students in the VP sequence who provided the correct response decreased when they performed the physical activity.

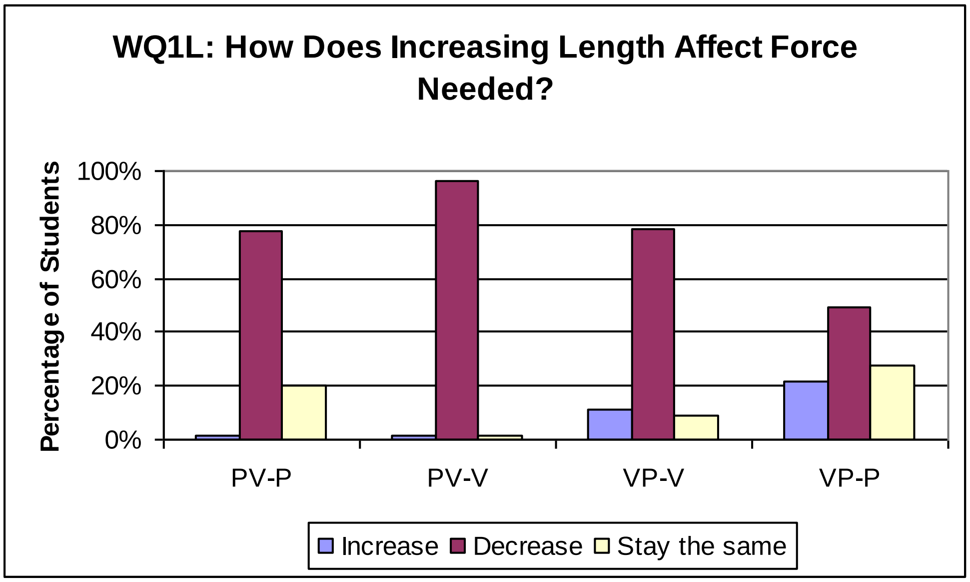
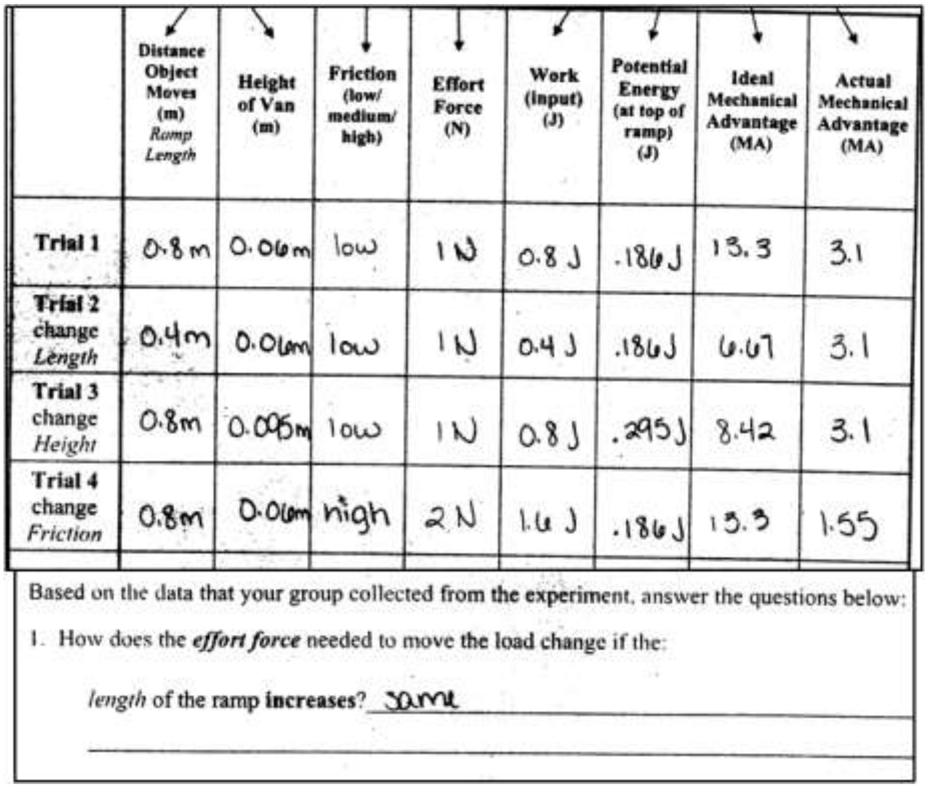


**Figure 7.18 PWF09 Inclined plane worksheet responses: WQ1L.**

It seems counterintuitive that the physical experiment caused fewer students to realize that a longer ramp required less force. One explanation is that students misread the spring scale. If this were the case, the students' data tables would contain inaccurate data, but their responses to the worksheet question would agree with the data table. Another explanation is that students had difficulty interpreting the data table. If this were the case, the students' data tables would contain accurate data but their worksheet response would not agree with the data table.

I inspected the data tables of several students who responded "stay the same" or "increase" and found evidence of both types of mistakes. Figure 7.19 below displays the data table of a student who recorded the same force needed to move the load for several lengths of ramp. This student responded that the force stayed the same when the ramp length was changed, which agrees with the data table. Figure 7.20 below displays the data table of a student who recorded accurate force measurements for various ramp lengths but incorrectly concluded that the force increased when the ramp length changed.



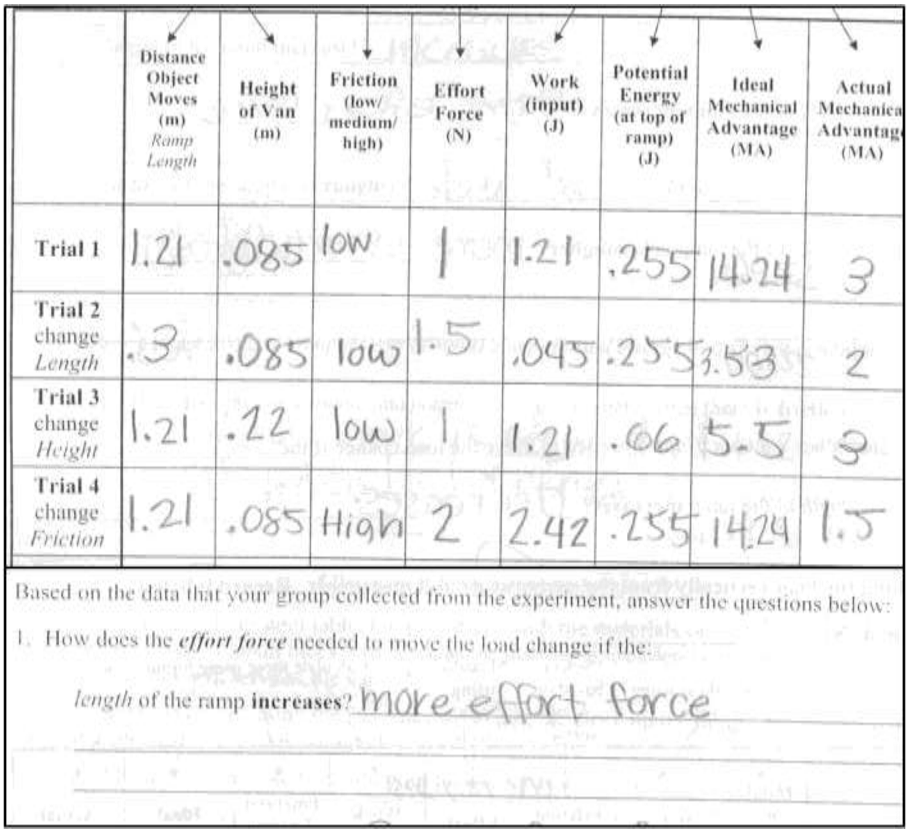
| | **Distance Object Moves (m)** *Ramp Length* | **Height of Van (m)** | **Friction (low/ medium/ high)** | **Effort Force (N)** | **Work (input) (J)** | **Potential Energy (at top of ramp) (J)** | **Ideal Mechanical Advantage (MA)** | **Actual Mechanical Advantage (MA)** |
|---|---|---|---|---|---|---|---|---|
| **Trial 1** | 0.8 m | 0.06 m | low | 1 N | 0.8 J | .186 J | 13.3 | 3.1 |
| **Trial 2** change *Length* | 0.4 m | 0.06 m | low | 1 N | 0.4 J | .186 J | 6.67 | 3.1 |
| **Trial 3** change *Height* | 0.8 m | 0.095 m | low | 1 N | 0.8 J | .295 J | 8.42 | 3.1 |
| **Trial 4** change *Friction* | 0.8 m | 0.06 m | high | 2 N | 1.6 J | .186 J | 13.3 | 1.55 |

Based on the data that your group collected from the experiment, answer the questions below:

1. How does the ***effort force*** needed to move the load change if the:

*length* of the ramp **increases**? same

Figure 7.19 Student recorded inaccurate data.



| | Distance Object Moves (m) *Ramp Length* | Height of Van (m) | Friction (low/ medium/ high) | Effort Force (N) | Work (input) (J) | Potential Energy (at top of ramp) (J) | Ideal Mechanical Advantage (MA) | Actual Mechanica Advantag (MA) |
|---|---|---|---|---|---|---|---|---|
| **Trial 1** | 1.21 | .085 | low | 1 | 1.21 | .255 | 14.24 | 3 |
| **Trial 2** change *Length* | .3 | .085 | low | 1.5 | .045 | .255 | 3.53 | 2 |
| **Trial 3** change *Height* | 1.21 | .22 | low | 1 | 1.21 | .66 | 5.5 | 3 |
| **Trial 4** change *Friction* | 1.21 | .085 | High | 2 | 2.42 | .255 | 14.24 | 1.5 |

Based on the data that your group collected from the experiment, answer the questions below:

1. How does the ***effort force*** needed to move the load change if the:

*length* of the ramp **increases**? more effort force

**Figure 7.20 Student recorded accurate data but drew incorrect conclusion.**

The second part of WQ1 asked, "How does the *effort force* needed to move the load change if the *height* of the ramp **increases**?" The scientifically correct response is that increasing the ramp's height increases the force needed. When a constant length ramp is made to reach a higher height, the steepness of the ramp increases. A steeper ramp requires more force to keep the object from sliding back down the ramp due to gravity.

As shown in Figure 7.21 below, the majority (more than 70%) of students responded that the force needed to move the object would increase if the height of the ramp increased. A smaller percentage (about 20% after the physical experiment in each sequence and less than 10% after the virtual experiment in each sequence) of students responded that the force needed would not change when the height changed. In addition, a few students in the VP sequence provided alternative responses; specifically, these students responded that changing the height changes the force needed to move the object. Overall, students more frequently found the correct relationship, that increasing height increases the force needed, while using the computer simulation. The highest percentage of students finding this relationship occurred in the PV sequence for the virtual activity. It is not clear why the virtual manipulative better helped students to identify this relationship.

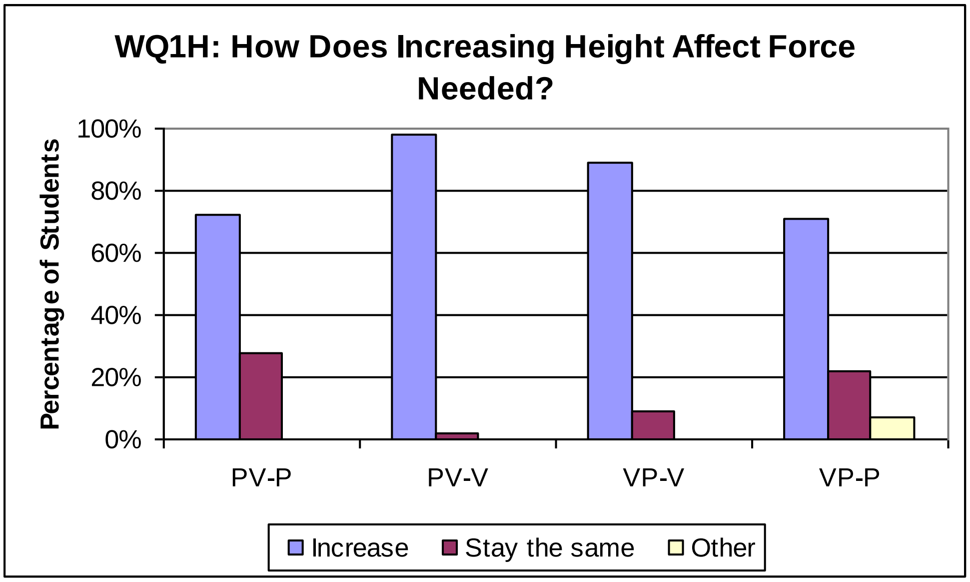


**Figure 7.21 PWF09 Inclined plane worksheet responses: WQ1H.**

The final part of WQ1 asked, "How does the *effort force* needed to move the load change if the *surface* of the ramp gets **rougher**?" The scientifically correct response is that increasing the surface roughness will increase the force needed. A rougher surface will have a higher coefficient of friction, so more applied force is needed to overcome the frictional force.

As shown in Figure 7.22 below, the majority (more than 75%) of students stated that making the surface of the ramp rougher would increase the force needed to move the object. Also as shown in Figure 7.22, a few students (about 6%) in the PV sequence responded that increasing the roughness of the surface would make the force needed decrease after performing the virtual experiment. In the VP sequence, a few students (about 15%) responded that increasing friction does not affect the force needed to lift the load after each experiment. A very small percentage of students in the PV sequence stated a few alternative answers during the physical activity, such as that they did not have enough information to determine how the surface affected the force needed (11% after physical experiment) and that changing the surface changes the force needed (4% after physical experiment). For both activities, students in the PV sequence were slightly more likely than students in the VP sequence to identify the correct relationship, that increasing the roughness increases the force needed. There is an increase in the percentage of students who identified this relationship for the second activity in both sequences.

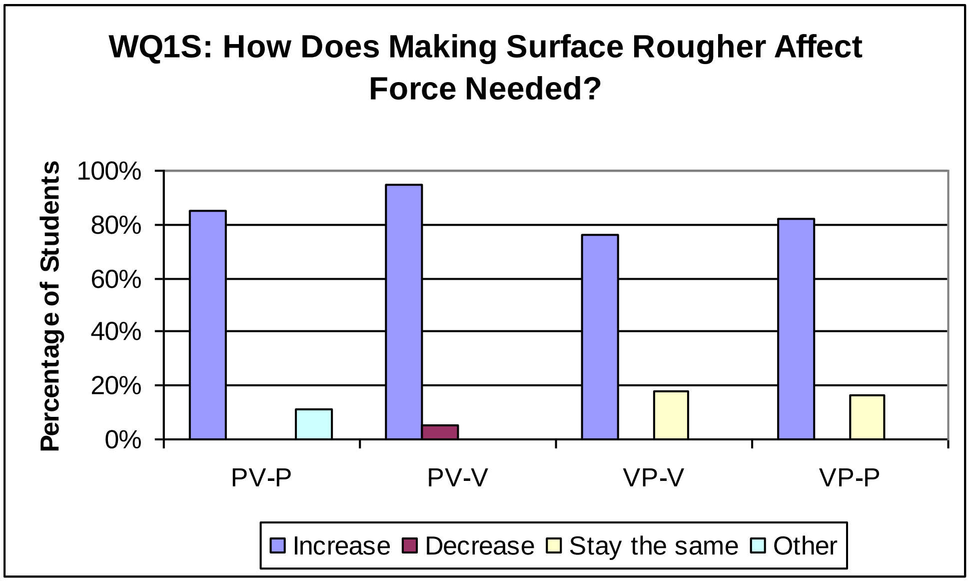


**Figure 7.22 PWF09 Inclined plane worksheet responses: WQ1S.**

### *7.2.1.2 WQ2: Work (Input)*

WQ2 referred to work (input). In the CoMPASS curriculum, work (input) is used to indicate the work required to lift the object. Work (output) is used to indicate the change in the object's potential energy during the lift; this would be the same as the minimum work needed to lift the object straight up. WQ2 asked the students how the work needed to lift the load would be affected if changes were made to the length, height and surface of the ramp. The most common responses are shown in the Figures 7.23, 7.24, and 7.27 below.

The first part of WQ2 asked, "How does the *work (input)* needed to move the load change if the *length* of the ramp **increases**?" For the ideal situation, changing the length of the inclined plane would not affect the work needed to lift the object because it is being lifted to the same height. In the physical experiment, students observed an increase in the work due to friction on the ramp's surface and fluctuations in the work due to error in performing the experiment.

As shown in Figure 7.23, students' responses about how changing the length of the ramp would affect the work needed to lift the object varied by sequence and activity. In the PV sequence, students most commonly (about 75%) stated that the work increased when length of the ramp increased after performing the physical experiment. However, after completing the virtual experiment, students in the PV sequence most commonly (about 80%) stated that the work did not change when the length of the ramp changed. This was also the most common response for students in the VP sequence for both activities (85% after virtual activity and 45% after physical activity). In both sequences, students were more commonly stated that the work did not change when the length changed after using the computer simulation. However, comparing responses from both sequences after the physical activity, students in the VP sequence more commonly stated that the length of the ramp did not affect the work than students in the PV did.

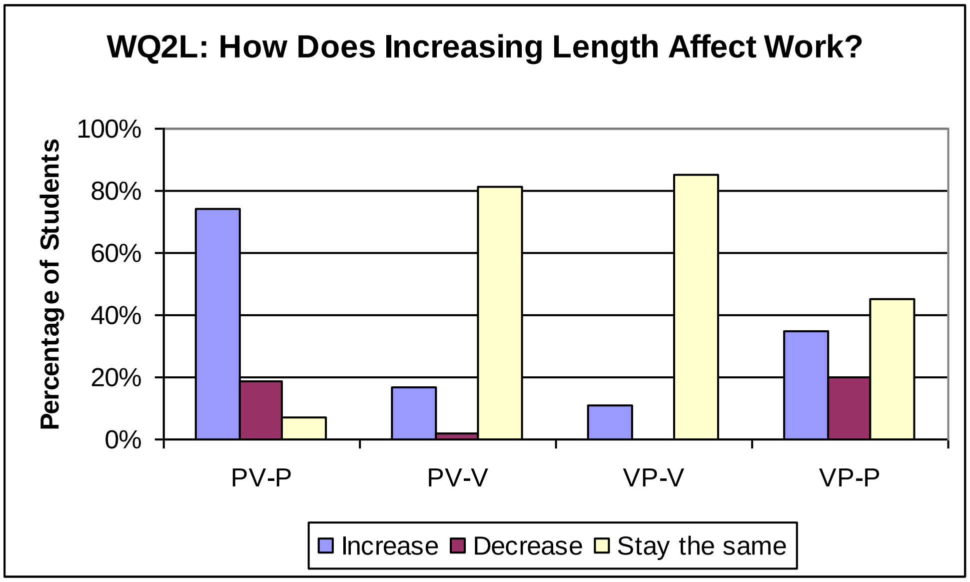


**Figure 7.23 PWF09 Inclined plane worksheet responses: WQ2L.**

The second part of WQ2 asked, "How does the *work (input)* needed to move the load change if the *height* of the ramp **increases**?" The scientifically correct response is that the work needed will increase when the height of the ramp is increased. When the height of the ramp is increased, the object must be lifted higher and will undergo a greater change in potential energy. Since work is equal to or greater than the change in potential energy, the work must also increase.

As shown in Figure 7.24 below, the majority of students stated that an increase in the ramp's height would cause an increase in the work needed to lift the load for all activities (more than 55%). In both sequences, students more frequently identified this relationship after performing the virtual activity than after performing the physical activity. A surprisingly large percentage of students stated that changing the height did not affect the work in each activity (about 10% to 30% across activities). Students more frequently identified this relationship in the physical activity than in the virtual activity. Some students made an incorrect conclusion from a correct data table, as shown in Figure 7.25 below, while other students had ambiguous data, as shown in Figure 7.26. In the physical experiment, students had to measure force with a spring scale, measure length with a meter stick and use the equation "work= force x distance" to find the work. A mistake could have occurred in any one of these steps. From their data tables, it is evident that many students did not make accurate measurements of force in the physical experiment (i.e. measured the same force for two ramp heights), which led to the interpretation that work did not change when height changed. The simulation directly reported a value of work for each trial.

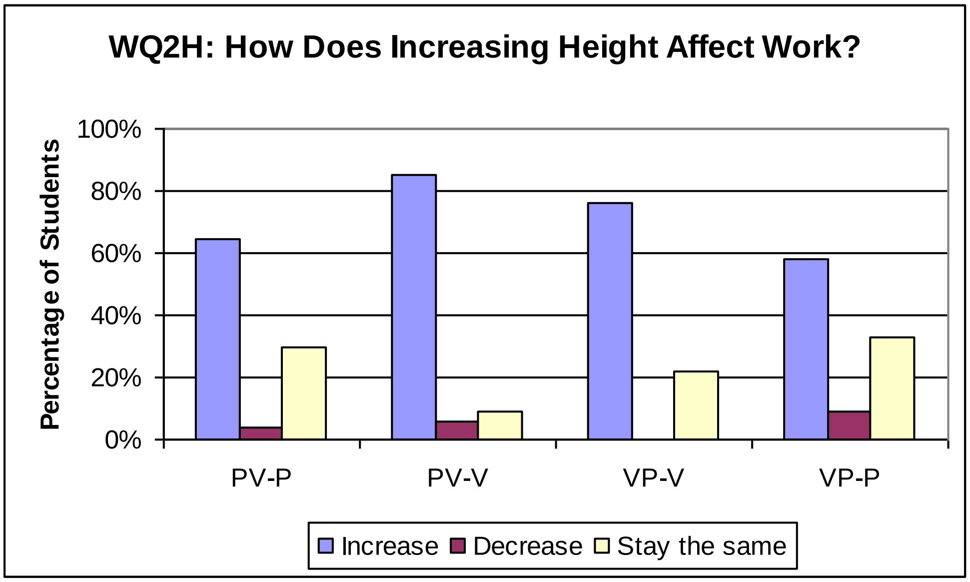
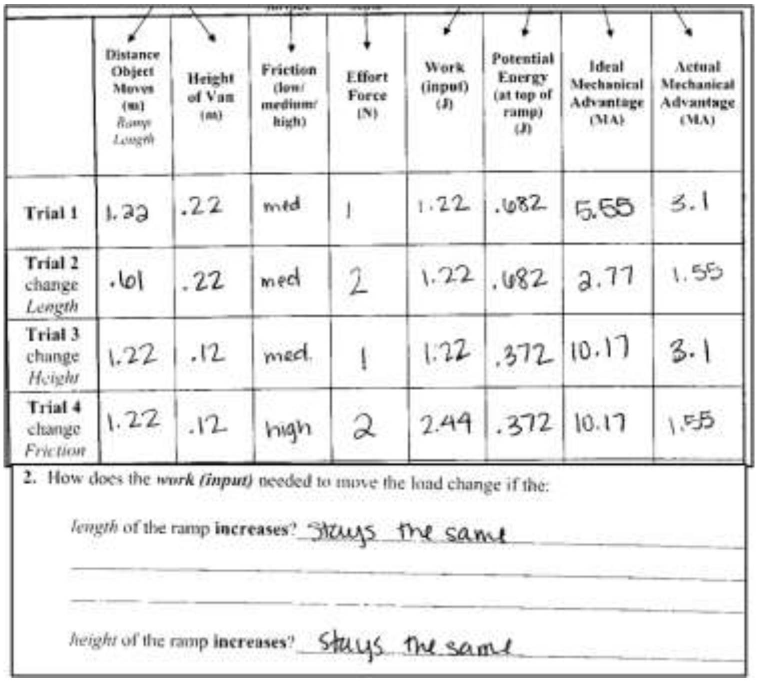


**Figure 7.24 PWF09 Inclined plane worksheet responses: WQ2H.**



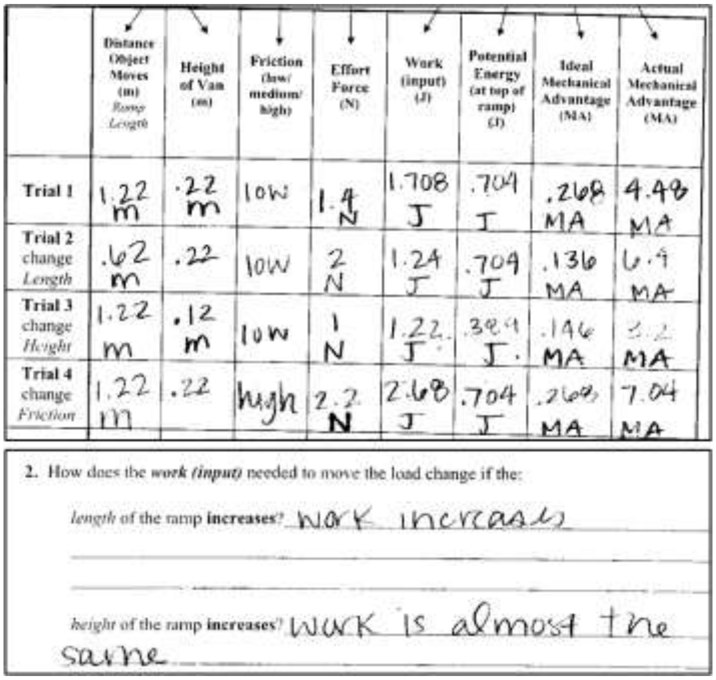
| | Distance Object Moves (m) *Ramp Length* | Height of Van (m) | Friction (low/ medium/ high) | Effort Force (N) | Work (input) (J) | Potential Energy (at top of ramp) (J) | Ideal Mechanical Advantage (MA) | Actual Mechanical Advantage (MA) |
|---|---|---|---|---|---|---|---|---|
| **Trial 1** | 1.22 | .22 | med | 1 | 1.22 | .682 | 5.55 | 3.1 |
| **Trial 2** change *Length* | .61 | .22 | med | 2 | 1.22 | .682 | 2.77 | 1.55 |
| **Trial 3** change *Height* | 1.22 | .12 | med. | 1 | 1.22 | .372 | 10.17 | 3.1 |
| **Trial 4** change *Friction* | 1.22 | .12 | high | 2 | 2.44 | .372 | 10.17 | 1.55 |

**2.** How does the ***work (input)*** needed to move the load change if the:

*length* of the ramp **increases**? Stays the same

*height* of the ramp **increases**? Stays the same

**Figure 7.25 Student draws incorrect conclusion from correct data.**



| | Distance Object Moves (m) *Ramp Length* | Height of Van (m) | Friction (low/ medium/ high) | Effort Force (N) | Work (input) (J) | Potential Energy (at top of ramp) (J) | Ideal Mechanical Advantage (MA) | Actual Mechanical Advantage (MA) |
|---|---|---|---|---|---|---|---|---|
| **Trial 1** | 1.22 m | .22 m | low | 1.4 N | 1.708 J | .704 J | .268 MA | 4.48 MA |
| **Trial 2** change *Length* | .62 m | .22 | low | 2 N | 1.24 J | .704 J | .136 MA | 6.9 MA |
| **Trial 3** change *Height* | 1.22 m | .12 m | low | 1 N | 1.22 J | .389 J | .146 MA | 3.2 MA |
| **Trial 4** change *Friction* | 1.22 m | .22 | high | 2.2 N | 2.68 J | .704 J | .268 MA | 7.04 MA |

**2.** How does the ***work (input)*** needed to move the load change if the:

*length* of the ramp **increases**? work increases

*height* of the ramp **increases**? work is almost the same

**Figure 7.26 Student draws consistent conclusion from inaccurate data.**

The final part of WQ2 asked, “How does the *work (input)* needed to move the load change if the *surface* of the ramp gets **rougher**?” The scientifically correct response is that increasing the surface roughness increases the work needed. More applied force is needed to overcome the increased frictional force, so over a constant length, the work (input) will be greater.

As shown in Figure 7.27 below, the majority (more than 85%) of students stated that an increase in surface roughness would lead to an increase in the work needed to lift the load. A small percentage of students responded that changing the surface roughness would not affect the work needed (about 10% after each experiment except physical experiment in PV sequence). In the PV sequence, a few students (7%) stated that they did not have enough information to determine how changing the surface would affect the work needed to lift the load. Looking just at the response that surface roughness would not affect the work needed, this response occurred in only the virtual, not the physical, experiment in the PV sequence. However, this response occurred in both the physical and virtual activities in the VP sequence. Thus, it is possible that the virtual activity is leading some students to believe that the surface roughness does not affect the work needed to lift a load.

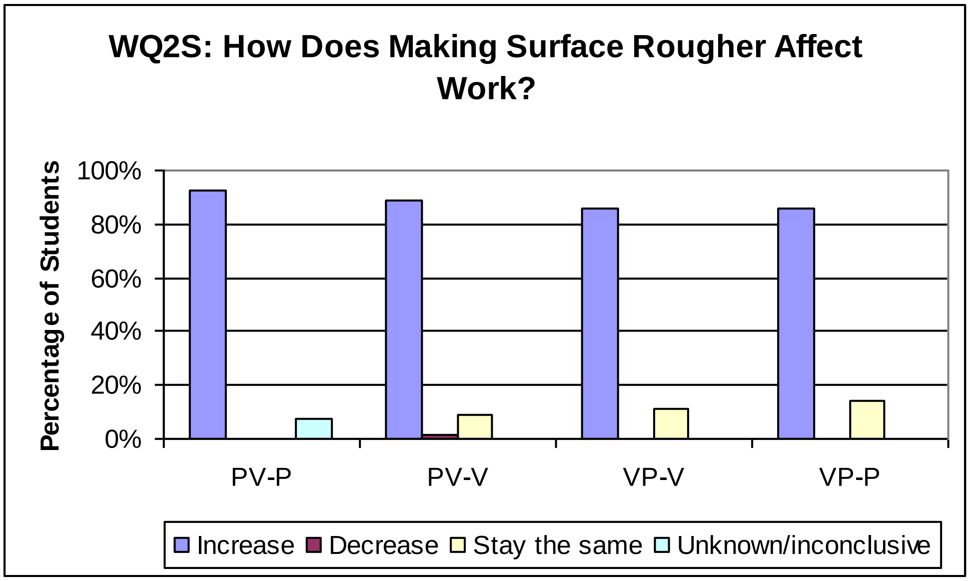


**Figure 7.27 PWF09: Inclined plane worksheet responses: WQ2S.**

### *7.2.1.3: WQ3: Potential Energy*

WQ3 asked students how the potential energy of the load at the top of the ramp would be affected by changes to the length, height and surface of the ramp. The most common responses are shown in the Figures 7.28, 7.29, and 7.30 below.

The first part of WQ3 asked, "How does the *potential energy* of the load at the top of the ramp change if the *length* of the ramp **increases**?" The scientifically correct response is that the length of the inclined plane does not affect the change in the object's potential energy. Potential energy depends on the mass of the object and its vertical distance from a reference point, which was taken as the bottom of the ramp in these experiments.

As shown in Figure 7.28 below, the vast majority (more than 90%) of students responded that the length of the ramp did not affect the potential energy for each activity. After performing the physical experiment in the PV sequence, a few students (9%) responded that increasing the length would increase the potential energy at the top of the ramp. After performing the physical experiment in the VP sequence, very few students (5%) stated that increasing the length would decrease the potential energy.

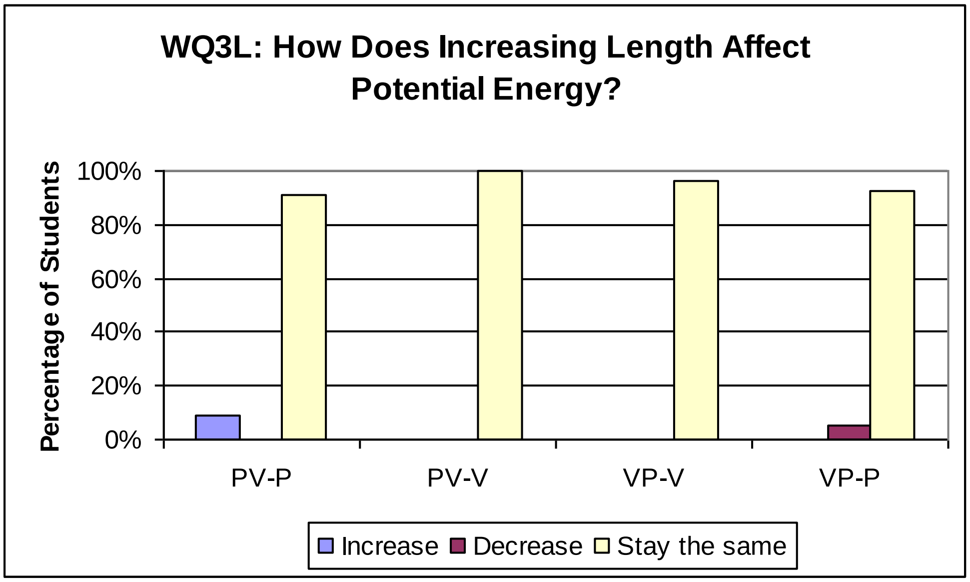


**Figure 7.28 PWF09 Inclined plane worksheet responses: WQ3L.**

The second part of WQ3 asked, "How does the *potential energy* of the load at the top of the ramp change if the *height* of the ramp **increases**?" The scientifically correct response is that the object will undergo a greater change in potential energy when the height of the inclined plane is increased. Since the object's potential energy depends on its vertical distance from a reference point, here taken to be the bottom of the ramp, increasing the height increases this distance, thereby increasing the change in potential energy.

As shown in Figure 7.29 below, the vast majority (more than 90%) of students responded that increasing the height of the ramp would increase the object's potential energy at the top of the ramp. After the virtual activity in each sequence, a few students (less than 10%) responded that increasing the height would decrease the potential energy. After each experiment except the physical activity in the VP sequence, very few students (5% or less) responded that the height does not affect the change in potential energy.

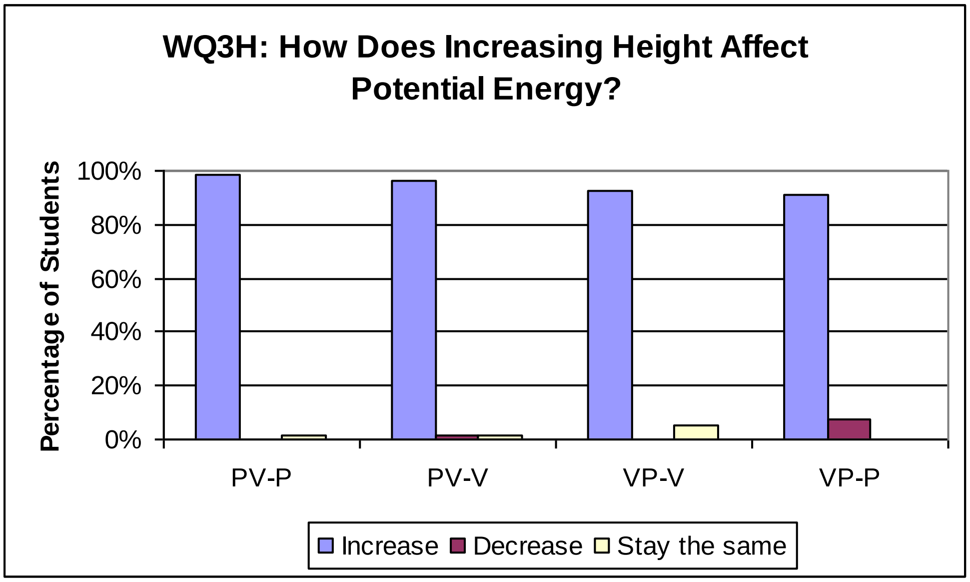


**Figure 7.29 PWF09 Inclined plane worksheet responses: WQ3H.**

The final part of WQ3 asked, "How does the *potential energy* of the load at the top of the ramp change if the *surface* of the ramp gets **rougher**?" The scientifically correct response is that changing the surface roughness does not affect the change in the object's potential energy. Since potential energy depends only on mass and height, the surface of the ramp does not have an effect.

As shown in Figure 7.30 below, the vast majority (about 90%) of students responded that changing the ramp's surface would not affect the potential energy at the top of the ramp. In the

PV sequence, a few students (about 5%) responded that increasing the roughness would increase the object's potential energy after performing the physical experiment and decrease the objects' potential energy after performing the virtual experiment. In the VP sequence, a few students (5%) responded that increasing friction increased the object's potential energy after each activity. In addition, in the PV sequence, a few students (6%) stated that they did not have enough information to determine how the surface affected the object's potential energy.

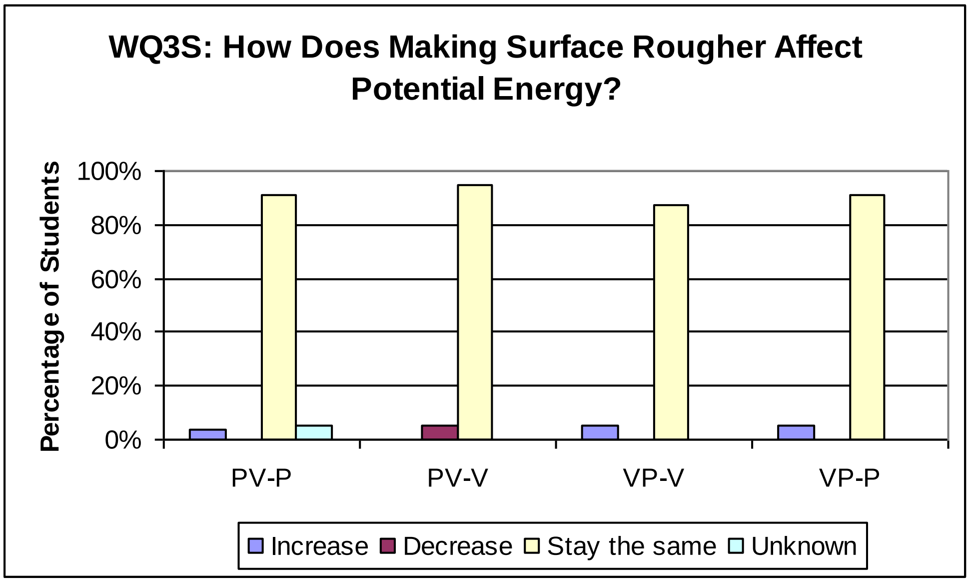


**Figure 7.30 PWF09 Inclined plane worksheet responses: WQ3S.**

### *7.2.1.4 WQ4: Comparison of work (input) and potential energy*

WQ4 asked students to compare the work (input) and potential energy for several conditions: friction is present, the surface gets smoother, and the surface is frictionless. The most common responses are shown in the Figures 7.31, 7.32 and 7.33 below.

The first part of WQ4 asked, "How do *work (input)* and *potential energy* compare when there **is friction**?" In the CoMPASS curriculum, work (input) is defined as the work needed to lift the load using the inclined plane. So defined, work (input) will always be greater or equal to the change in the object's potential energy. With friction present, the work (input) will be greater than the potential energy,

As shown in Figure 7.31 below, students' responses differed between the two sequences. In the VP sequence, students most commonly (about 45%) responded that work (input) would be greater than potential energy after each experiment. This response was provided by only about 20% of students in the PV sequence after each activity. In the PV sequence, the most common response (about 55%) was that the work would increase while the potential energy would remain the same. These students seem to have interpreted the question to ask, “What would happen to the work and potential energy if friction were present?” since they discussed work and potential energy separately. While the information provided by these students is not incorrect, they failed to make the comparison asked for in the question. In both sequences, a few students (15% or less) responded that work would be equal to potential energy; this answer is true only for the frictionless case. A few students gave alternative answers, such as work and potential energy both increase, work changed and potential energy stays the same, work and potential energy both decrease, and potential energy increases while work stays the same.

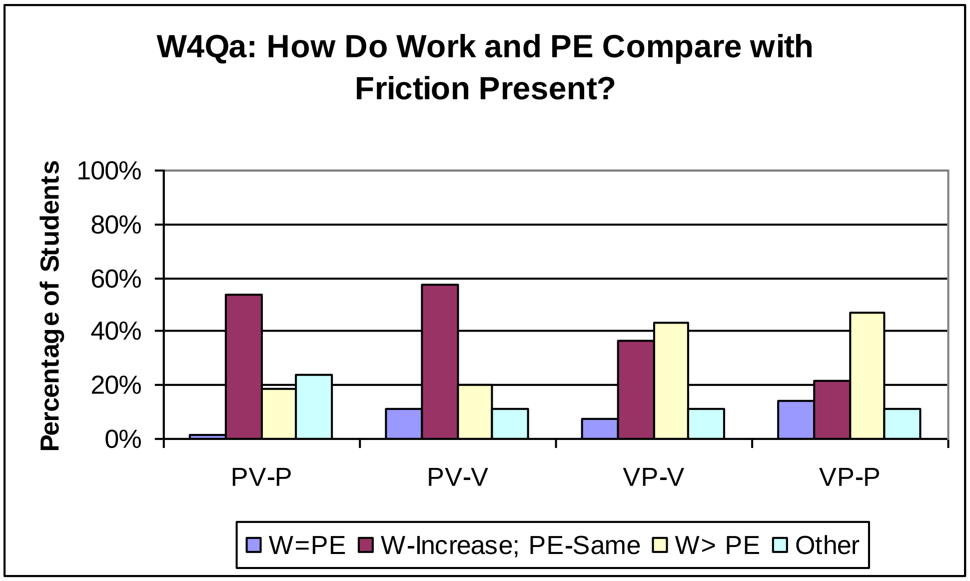


**Figure 7.31 PWF09 Inclined plane worksheet responses: WQ4a.**

The second part of WQ4 asked, “How does the relationship between *work (input)* and *potential energy* change as the surface gets **smoother**?” The intent of this question was for students to discuss that the work value got closer to the potential energy value as the surface got smoother. With a smoother surface, less applied force is required to overcome the frictional force, reducing the work (input). Surface does not affect the change in the object’s potential energy. Thus, the work becomes closer to the potential energy.

Again, students' responses differed between the two sequences, as shown in Figure 7.32 below. In the VP sequence, the most common (about 40%) response after each activity was the intended response, that work became closer to potential energy. This response was provided by less than 20% of students in the PV sequence after each activity. In the PV sequence, the most common (about 55% after physical activity and 45% after virtual activity) response was that the work would decrease while the potential energy would not change. Again, these students seem to be interpreting the question to ask "What would happen to the work and potential energy if the surface got smoother?" The information these students provided is correct, but does not address the comparison of work and potential energy the question was designed to elicit. In both sequences, some students responded that the work would be equal to the potential energy, which is correct only for the frictionless case. This response was provided by about 25% of students after each activity in the VP sequence and after the virtual activity in the PV sequence, but by only 6% of students after the physical activity in the PV sequence. Students provided a variety of other responses, including: work stays the same and potential energy increases; work decreases; work decreases and potential energy increases; potential energy stays the same; work and potential energy decrease; work increases and potential energy stays the same; and work is less than potential energy.

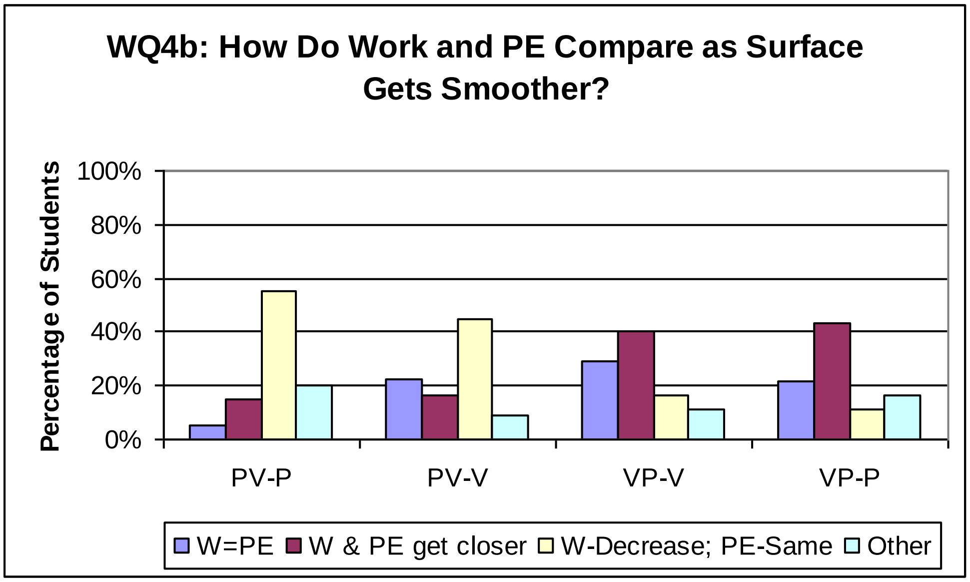


**Figure 7.32 PWF09 Inclined plane worksheet responses: WQ4b.**

The final part of WQ4 asked, “How does the *work (input)* and *potential energy* compare when there is **no friction**?” For a frictionless surface, the work needed to lift the object using a ramp is due only to change in the object’s height. Thus, the work (input) would be equal to the change in the object’s potential energy.

As shown in Figure 7.33 below, the most common response differed between the two sequences. In the VP sequence, the majority (more than 80%) of students responded that the work and potential energy would be equal for both the physical and virtual activities. In the PV sequence, the most common response after students performed the physical experiment was that work would decrease, while potential energy would not change (provided by about 40% of students). Again, students providing this response seem to be interpreting the question to ask “What would happen to the work and potential energy if the ramp had no friction?” After the students in the PV sequence performed the virtual activity, the majority (about 75%) of students responded that work and potential energy would be equal. Students provided a variety of other answers, including: neither work nor potential energy change; work gets closer to potential energy; work increases and potential energy stays the same; and potential energy not affected.

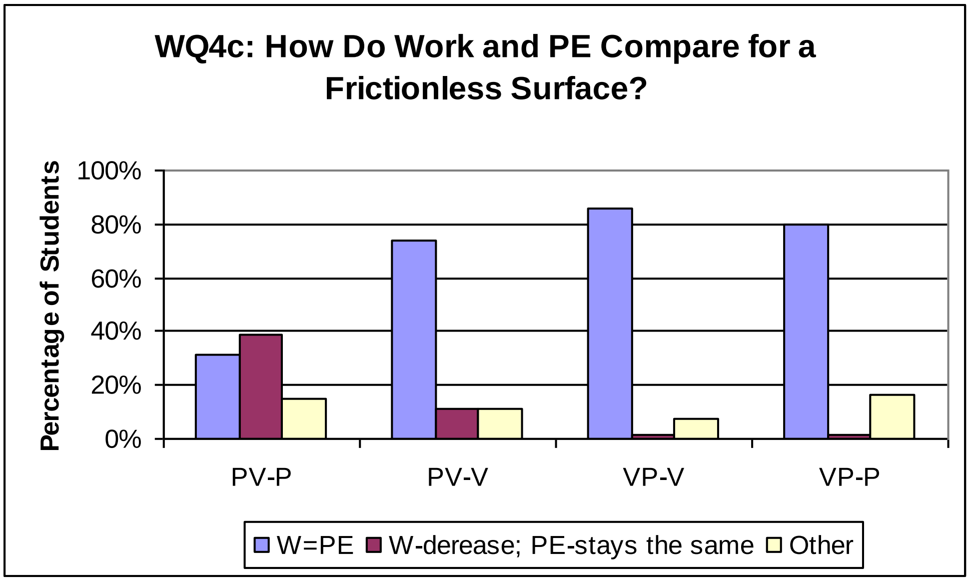


Figure 7.33 PWF09 Inclined plane worksheet responses: WQ4c.

#### *7.2.1.5 WQ5: Ideal Mechanical Advantage*

WQ5 asked students how the ideal mechanical advantage (IMA) would be affected if changes were made to the length, height and surface of the ramp. Students' responses are shown in Figures 7.34, 7.35 and 7.36 below.

The first part of WQ5 asked, "How does the *ideal mechanical advantage* change if the *length* of the ramp **increases**?" Mechanical advantage is a measure of how much the inclined plane reduces the applied force needed to lift the load. The IMA is calculated by dividing the length of the ramp by its height. Thus, increasing the length of the ramp increases the IMA. Physically, this makes sense since a longer ramp requires less applied force to lift the load.

As shown in Figure 7.35, the majority (65% or more) of students responded that increasing the length of the ramp would increase the ideal mechanical advantage. In the VP sequence, students more frequently stated that increasing the length decreased the IMA (13% after the virtual experiment and 29% after the physical experiment) than did students in the PV sequence (less than 5% after each activity). These students had misinterpreted a correct data table (i.e. data table showed IMA increased when length increased, but students reported IMA decreased when length increased). It is possible that students are less aware of the direction in which they have changed the length in simulation since they are not physically replacing a longer board with a shorter board. When the students changed the length, the IMA decreased, but it was because they had decreased the length. In the PV sequence, a few students (6%) responded that increasing the length would make the IMA change after performing the physical experiment.

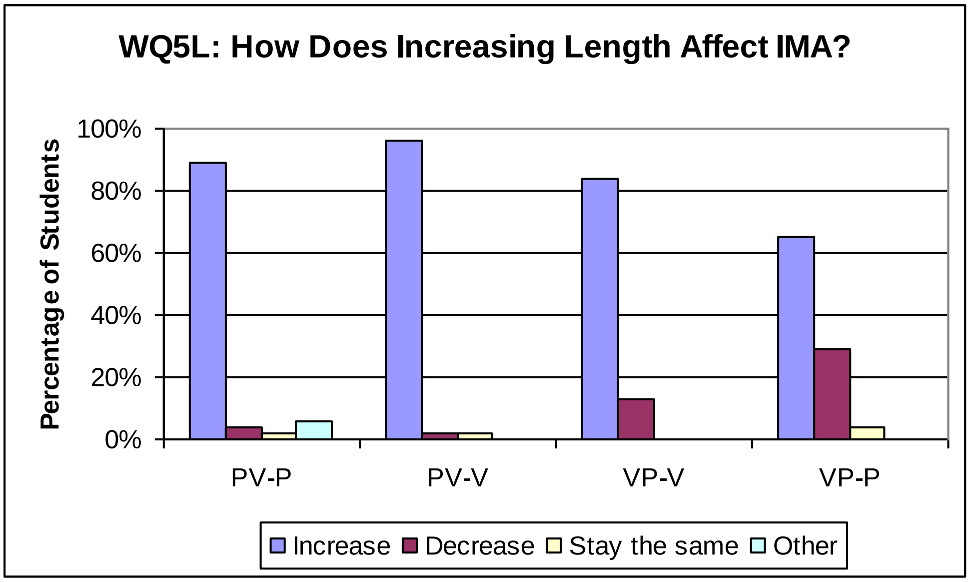


**Figure 7.34 PWF09 Inclined plane worksheet responses: WQ5L.**

The second part of WQ5 asked, “How does the *ideal mechanical advantage* change if the *height* of the ramp **increases**?” As described above, the IMA is calculated by dividing the length of the inclined plane by its height. Thus, increasing the height decreases the IMA. Physically, this makes sense since a steeper ramp requires more force to lift a load than a shorter ramp of the same length.

As shown in Figure 7.35, the majority (about 80%) of students responded that increasing the height of the ramp would decrease the ramp’s ideal mechanical advantage. A few students responded that the ramp’s IMA would increase (about 10%) or stay the same (about 5% after virtual activity only) if the height were increased. A few students (4%) in the PV sequence stated that the height would make the IMA change. Students’ responses appear to be consistent across both treatments and both the physical and virtual activities.

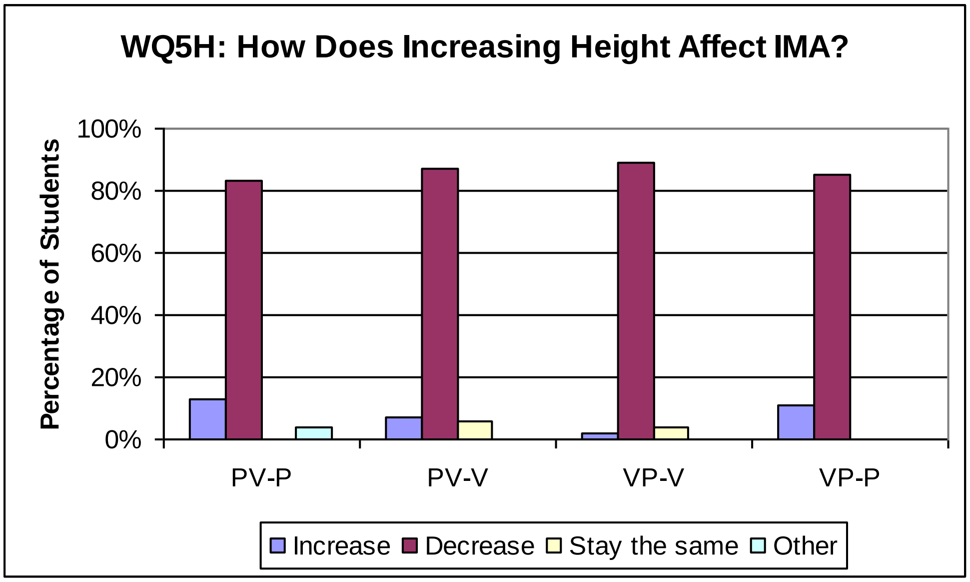


**Figure 7.35 PWF09 Inclined plane worksheet responses: WQ5H.**

The final part of WQ5 asked, “How does the *ideal mechanical advantage* change if the *surface* of the ramp gets **rougher**?” Because the IMA depends only on the height and length of the inclined plane, it does not change when the surface is changed. This is the difference between ideal and actual mechanical advantage.

As shown in Figure 7.36 below, the majority (70% or more) of students responded that changing the surface roughness of the ramp would not affect they ramp’s ideal mechanical advantage. Students in the PV sequence more frequently responded that increasing friction decreased IMA (13% after physical experiment and 26% after virtual experiment) than did students in the VP sequence (11% after virtual experiment and 4% after physical experiment). Some students (less than 10%) responded that increasing the surface roughness would increase the ramp’s IMA.

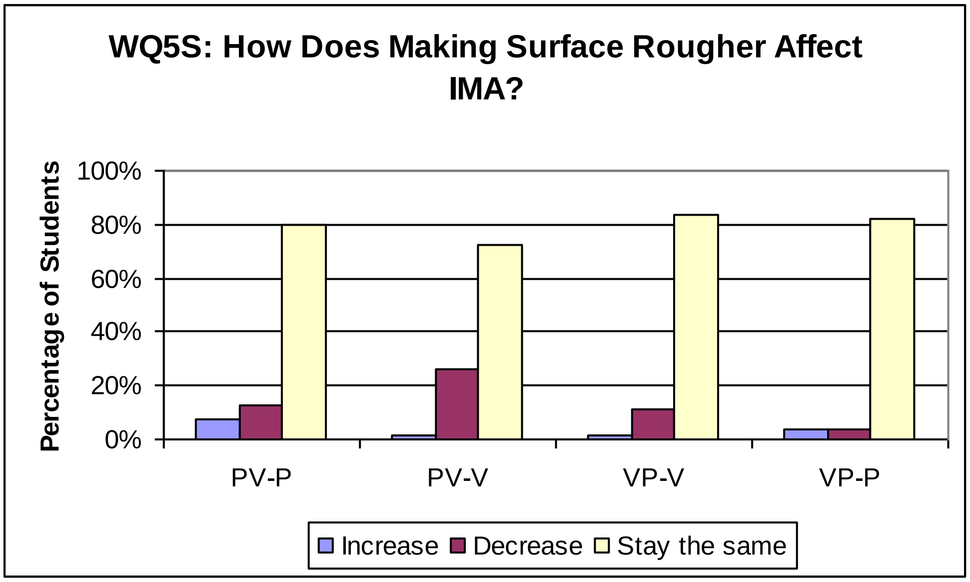


**Figure 7.36 PWF09 Inclined plane worksheet responses: WQ5S.**

#### *7.2.1.6 WQ6: Actual mechanical advantage*

WQ6 asked students how the ramp's actual mechanical advantage (AMA) would change if changes were made to the ramp's length, height and surface. Students' responses are displayed in Figures 7.37, 7.38 and 7.40 below.

The first part of WQ6 asked, "How does the *actual mechanical advantage* change if the *length* of the ramp **increases**?" Mechanical advantage is a measure of how much the inclined plane reduces the applied force needed to lift a load. AMA is calculated by dividing the applied force needed by the gravitational force (weight) on the object. A longer ramp requires less applied force than a shorter ramp, so the AMA would increase.

As shown in Figure 7.38, the majority of students responded that the ramp's actual mechanical advantage would increase if the length were increased, although the percentage of students providing this response varied from 42% to 91% across activities. Some students responded that the AMA would decrease or not change if the length were increased, with the percentage of students providing this response varying from 6% to 27% across activities. In both activities, students in the PV sequence more frequently identified the correct relationship that increasing the length would increase the AMA than students in the VP sequence did. However, within each sequence, students were more frequently identified this relationship in the virtual activity. Students in the VP sequence appeared to have difficulty with this question after completing the physical experiment. Students who reported an incorrect relationship in the virtual activity appeared to have difficulty with the simulation; several students recorded non-physical values of actual mechanical advantage (i.e. actual mechanical advantage is zero for all ramps tested). Students who reported an incorrect relationship in the physical activity appeared to have had difficulty making accurate force measurements (i.e. recorded the same value of force for two lengths of inclined planes), which made their calculations show that length did not affect actual mechanical advantage.

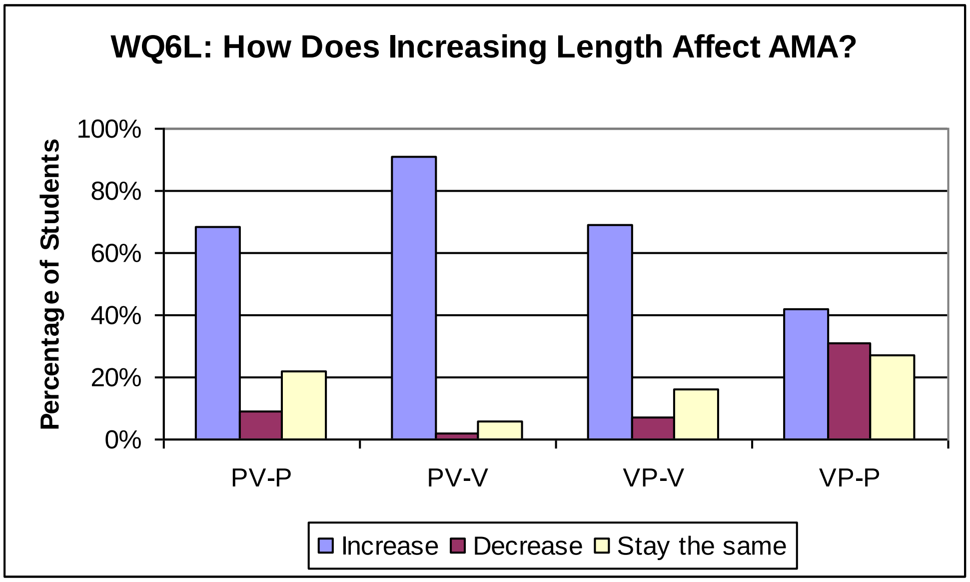


**Figure 7.37 PWF09 Inclined plane worksheet responses: WQ6L.**

The second part of WQ6 asked, "How does the *actual mechanical advantage* change if the *height* of the ramp **increases**?" As previously stated, the AMA is calculated by dividing the applied force needed by the object's weight. A steeper inclined plane requires more applied force to lift the load, so it will have less AMA than a lower, less steep inclined plane.

As shown in Figure 7.38, the majority of students responded that increasing the ramp's height would decrease the ramp's actual mechanical advantage (about 60% to 75% across activities). Some students responded that increasing the height would increase the AMA (15% or less) or not change the AMA (7% to 28% across activities). Students more frequently (about 25%) stated that the AMA would not change with the height for the physical activities in both sequences.

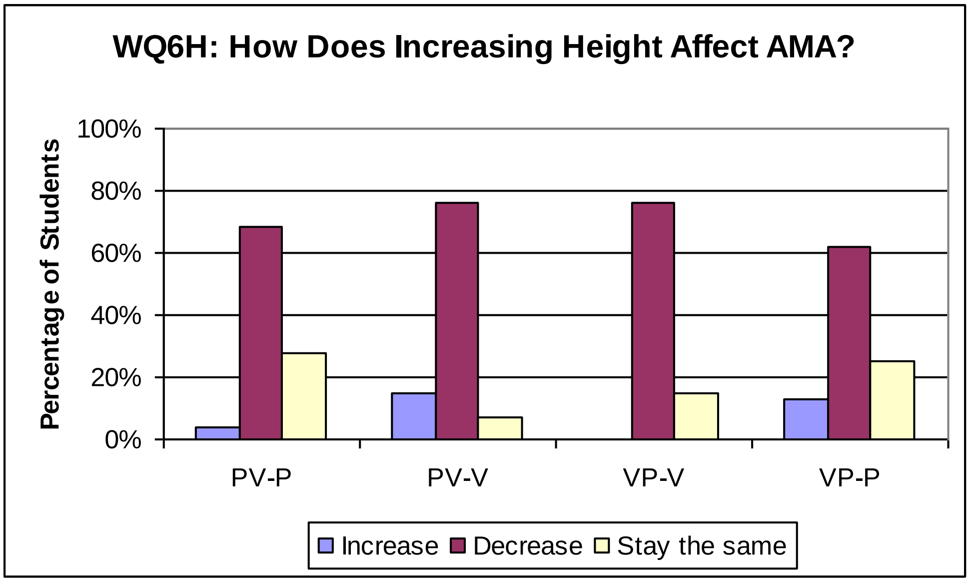


**Figure 7.38 PWF09 Inclined plane worksheet responses: WQ6H.**

The final part of WQ6 asked, “How does the *actual mechanical advantage* change if the *surface* of the ramp gets **rougher**?” A rougher ramp will require more applied force to lift a load than a smoother ramp because a greater frictional force must be overcome. Since AMA is calculated by dividing the applied force by the load’s weight, a rougher ramp has less AMA than a smoother ramp.

As shown in Figure 7.39 below, the majority (70% or more) of students responded that increasing the surface roughness of the ramp would decrease the actual mechanical advantage. Some students responded that increasing the roughness would increase the AMA (about 10% except after virtual activity in VP sequence)or not change the AMA (about 20% except are physical experiment in PV sequence). Students more frequently responded that the surface roughness would not affect the AMA after completing the virtual experiment. Students more frequently correctly identified the relationship that increasing the surface roughness would decrease the AMA in the PV sequence after performing just the physical experiment. When the students in the PV sequence moved on to the virtual experiment, a lower percentage of students provided this response. As described above, students in the PV sequence appear to have had difficulty getting actual mechanical advantage readings from the simulation (i.e. recorded zero mechanical advantage for all ramps), while some students had difficulty making accurate force measurements in the physical experiment (i.e. recorded the same force for two surfaces).

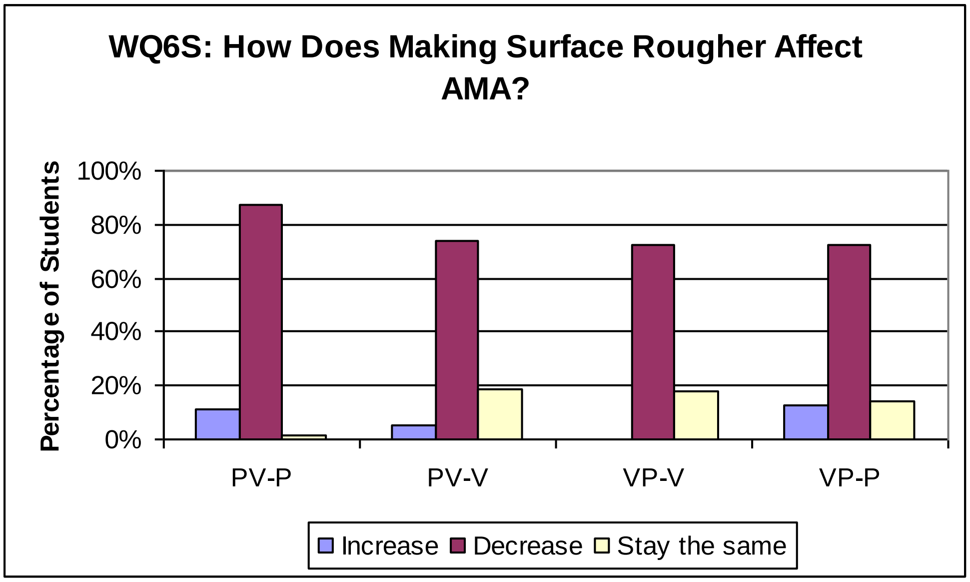


**Figure 7.39 PWF09 Inclined plane worksheet responses: WQ6S.**

### *7.2.2. Chi-square Analysis of Worksheet Responses*

The data analysis responses given by students in the PV and VP sequences were compared using a chi-square test for independence. A significant chi-square test result indicates that the responses likely came from two different populations. If the number of students expected to give a certain response in any treatment was less than five, Fisher's exact test was used. Comparisons where Fisher's exact test was used are indicated with a symbol ($^+$) in Table 7.2 below. Two comparisons were made for each question. As such, the p-value to indicate significance was divided by two; only comparisons with p-values less then 0.025 were taken to indicate a significant difference in responses between students in the PV and VP sequences. This was done to lower the chances of making a Type 1 error (incorrectly determining a significant difference), which is increased when multiple tests are performed on the same data (Everitt, 1992). For each question with a significant difference, the adjusted residuals were examined to identify which cells were significant. An adjusted residual greater than 1.96 was taken to indicate a significant cell (Haberman, 1973).

There are four possible comparisons to be made between the responses provided by students in the PV and VP sequences: responses after the first experiment in each sequence (PV physical responses compared to VP virtual responses), responses after the second experiment in each sequence (PV virtual responses compared to VP physical responses), each sequence's responses to the physical experiment (PV physical responses compared to PV virtual responses), and each sequence's responses to the virtual experiment (PV virtual responses compared to VP virtual responses). I have chosen to focus on the two comparisons that are most relevant to my research questions and, in my opinion, to the physics education community.

The first comparison (First Experiment) was between the responses given to the data analysis questions after the first experiment. Thus, the responses given after performing the physical experiment in the PV sequence were compared to the responses given after performing the virtual experiment in the VP sequence. This comparison assesses what students are learning from performing experiments with each manipulative type and addresses Research Question 1.

The second comparison was between the responses given to the data analysis questions after performing the physical experiment in both sequences. In this comparison, the students in the VP sequence have had prior experience with the experiment performed with the simulation. This comparison assesses whether the prior virtual experience influenced how students interpreted the data from the physical experiment. This information is likely of interest to physics educators because it provides advice about how to help successfully perform and analyze physical experiments.

Several of the contrasts revealed significant differences between the types of responses given by students in the PV and VP sequences, as shown in the table below. With the exception of Q6F, the questions with significant differences are discussed in detail below. Possible reasons for these differences are described in the following section. Q6F is omitted because the difference was in the type of incorrect answers students provided.

## Table 7.2 PWF09 Inclined Plane Worksheet Analysis Statistics

| | | | **First Experiment** (PV physical responses compare to VP virtual responses) | | | **Physical Experiment** (PV physical responses compared to VP physical responses) | | |
|---|---|---|---|---|---|---|---|---|
| **Q** | **Concept** | **Parameter** | **$\chi^2$*** | **p**** | **V***** | **$\chi^2$*** | **p**** | **V***** |
| Q1L | Force | Length | $\chi^2$(2, N=108) =5.6$^+$ | .047 | .23 | $\chi^2$(2, N=108) =13.2 | **.001** | .35 |
| 1H | Force | Height | $\chi^2$(1, N=108) =6.1 | **.013** | .24$^+$ | $\chi^2$(2, N=108) =4.0 | .143 | .19 |
| Q1S | Force | Surface | $\chi^2$(1, N=106) =17.5$^+$ | **<.001** | .40 | $\chi^2$(1, N=108) =16.0$^+$ | **<.001** | .38 |
| Q2L | Work | Length | $\chi^2$(2, N=108) =69.4 | **<.001** | .80 | $\chi^2$(2, N=108) =20.1 | **<.001** | .43 |
| Q2H | Work | Height | $\chi^2$(3, N=108) =3.8$^+$ | .222 | .19 | $\chi^2$(3, N=108) =2.3$^+$ | .547 | .15 |
| Q2S | Work | Surface | $\chi^2$(2, N=107) =9.9$^+$ | **.002** | .30 | $\chi^2$(1, N=108) =12.1$^+$ | **<.001** | .33 |
| Q3L | PE | Length | $\chi^2$(1, N=107) =5.1$^+$ | .057 | .22 | $\chi^2$(2, N=108) =7.5$^+$ | **.014** | .26 |
| Q3H | PE | Height | $\chi^2$(1, N=108) =1.0$^+$ | .618 | .10 | $\chi^2$(1, N=108) =4.2$^+$ | .118 | .20 |
| Q3S | PE | Surface | $\chi^2$(2, N=105) =2.8$^+$ | .287 | .16 | $\chi^2$(2, N=107) =2.9$^+$ | .286 | .16 |
| Q4A | Work/PE | Rough | $\chi^2$(3, N=108) =12.2$^+$ | **.005** | .34 | $\chi^2$(3, N=108) =21.3$^+$ | **<.001** | .44 |
| Q4B | Work/PE | Smoother | $\chi^2$(3, N=108) =28.5 | **<.001** | .51 | $\chi^2$(3, N=108) =29.4 | **<.001** | .52 |
| Q4C | Work/PE | No friction | $\chi^2$(2, N=108) =38.7 | **<.001** | .60 | $\chi^2$(2, N=107) =31.4 | **<.001** | .54 |
| Q5L | Ideal MA | Length | $\chi^2$(3, N=107) =6.2$^+$ | .058 | .24 | $\chi^2$(3, N=108) =16.3$^+$ | **<.001** | .39 |
| Q5H | Ideal MA | Height | $\chi^2$(3, N=106) =7.8$^+$ | **.017** | .27 | $\chi^2$(2, N=107) =1.8$^+$ | .558 | .13 |
| Q5S | Ideal MA | Surface | $\chi^2$(2, N=107) =1.9$^+$ | .477 | .13 | $\chi^2$(2, N=103) =3.1$^+$ | .256 | .17 |
| Q6L | Actual MA | Length | $\chi^2$(2, N=105) =.5$^+$ | .810 | .07 | $\chi^2$(2, N=108) =10.7 | **.005** | .31 |
| Q6H | Actual MA | Height | $\chi^2$(2, N=104) =3.9$^+$ | .109 | .19 | $\chi^2$(2, N=108) =2.9$^+$ | .280 | .16 |
| Q6S | Actual MA | Surface | $\chi^2$(2, N=104) =14.1$^+$ | **<.001** | .37 | $\chi^2$(2, N=108) =6.0$^+$ | .063 | .24 |

*The format is $\chi^2$(degrees of freedom, N) = chi-square statistic

**Significance value

***Effect size

Students in the PV sequence provided more correct interpretations of the physical data to Q1L, Q5L and Q6L as shown in Table 7.2 above. In Q1L, students were asked to describe how increasing the length of the inclined plane would affect the force needed to lift the load. Students' responses fell into the categories "force would decrease", "force would stay the same", and "force would increase". After performing the physical experiment, significantly more students in the PV sequence stated that the force would decrease, while significantly more students in the VP sequence indicated that the force would increase.

In Q5L, students were asked to describe how increasing the length of the inclined plane would affect the ideal mechanical advantage (IMA). Students' responses fell into the categories "IMA would increase", "IMA would decrease", "length does not affect IMA", and "other". After performing the physical experiment, significantly more students in the PV sequence stated that the ideal mechanical advantage would increase, while significantly more students in the VP sequence responded that IMA would decrease.

In Q6L, students were asked to describe how increasing the length of the inclined plane would affect the actual mechanical advantage. Students' responses fell into the categories "actual mechanical advantage would increase", "actual mechanical would advantage stay the same" and "actual mechanical advantage would decrease". After performing the physical experiment, significantly more students in the PV sequence responded that increasing the length would increase the actual mechanical advantage, while significantly more students in the VP sequence responded that increasing the length would decrease the actual mechanical advantage.

Students in the VP sequence gave more correct or more useful interpretations of the data on many questions and in both the contrasts between the first experiment responses and the physical data responses as shown in Table 7.2 above. In Q1H, students were asked to describe how increasing the height of an inclined plane would affect the force needed to lift a load. Students' responses fell in the categories "force would increase" and "force would stay the same". After the first experiment, students in the VP sequence were more likely to respond that increasing the height would cause the force to increase, while students in the PV sequence were more likely to say that increasing the height did not affect the force.

Q2L asked students to describe how increasing the length of the inclined plane affected the work needed to move the load. There was a significant difference in responses between the two sequences in both the first experiment and physical data contrasts. Students' responses fell in the categories "work would increase", "work would stay the same", and "work would decrease". After performing their first experiment, students in the VP sequence were more likely to respond that changing length would not change work, while students in the PV sequence were more likely to say increasing length would cause the work needed to increase. This is not surprising since students in the PV sequence performed the experiment with friction present, while students in the VP sequence performed the experiment in the simulation, which allowed them to investigate the frictionless case. However, the comparison between the PV and VP sequence responses to the physical data reveals that the prior virtual experience provided in the VP sequence allowed students to make a more useful interpretation of the physical data. In this contrast, students in the VP sequence were more likely to respond that changing length would not affect work, while students in the PV sequence were more likely to respond that increasing length would increase or decrease the work needed.

In Q3L, students were asked to describe how changing the length of the inclined plane affected the load's potential energy. Students' responses fell into the categories "potential energy would stay the same", "increasing length would decrease potential energy", and "increasing length increases potential energy". In the comparison between responses given after the physical experiment in each sequence, students in the PV sequence were more likely to state that increasing the length would increase the potential energy. Unlike Q2L, students in both sequences should have had the same values for potential energy as all students calculated potential energy based on the load and the distance the load was lifted.

In Q4, the students were asked to compare work and potential energy for three different types of surfaces. The responses given by students in the PV and VP sequences were significantly different for all three questions for both the first experiment and physical data contrasts. In Q4A, students were asked how work and potential energy compare when there is friction present. Students' responses fell into the categories "work is greater than potential energy", "work is equal to potential energy", "work increases and potential energy stays the same" and "other". After performing the first experiment, students in the VP were more likely to respond that work would be greater than potential energy, while students in the PV sequence were more likely to provide a different response ("other"). In the physical data contrast, students in the VP sequence were more likely to respond that work would be greater than or equal to the potential energy, while students in the PV sequence were more likely to respond that work would increase and potential energy would remain the same.

In Q4B, students were asked how work and potential energy compare when the surface gets smoother. Students' responses fell into the categories "work and potential energy get closer", "work is equal to potential energy", "work decreases and potential energy stays the same" and "other". In both the first experiment and physical data comparisons, students in the VP sequence were more likely to respond that work and potential energy would get closer or be equal, while students in the PV sequence were more likely to respond that work would decrease and potential energy would stay the same.

In Q4C, students were asked to compare work and potential energy for a frictionless inclined plane. Students' responses fell into the categories "work is equal to potential energy", "work decreases and potential energy stays the same", and "other". After performing the first experiment, students in the VP sequence were more likely to respond that work would be equal to potential energy, while students in the PV sequence were more likely to respond that work would decrease and potential energy would stay the same or to provide a different response ("other"). In the physical data comparison, students in the VP sequence were more likely to respond that work and potential energy would be equal, while students in the PV sequence were more like to respond that work would decrease and potential energy would stay the same.

In Q5H, students were asked to describe how increasing the height of the inclined plane changed the ideal mechanical advantage (IMA). Students' responses fell into the categories "IMA decreased", "IMA increased", "IMA did not change" and "other". In the comparison between responses provided after the first experiment in each sequence, students were more likely to respond that increasing the height increased the IMA than were students who performed the virtual activity first. It is possible that students were thinking about the affect of changing the length rather than the height, as discussed in the previous section.

Students in the PV and VP sequences gave different incorrect responses to several questions both in the comparison between responses provided after the first experiment and the after the physical experiment in each sequence. In Q1S, students were asked to describe how making the surface of the inclined plane rougher would affect the force needed to lift the load. Students' responses fell into the categories "force would increase", "force would stay the same", "force would decrease" and "other". While there was no difference between the numbers of students providing the physically correct response (i.e. force would not change), in both comparisons, students in the VP sequence were more likely to respond that force would stay the same while students in the PV sequence were more likely to provide an alternate response (“other”).

Similarly, in Q2S, students were asked to describe how making the surface rougher would affect the work needed to lift the load. Students’ responses fell into the categories “work would increase”, “work would stay the same” and “other”. Again, while there was no difference between the numbers of students providing the physically correct response (i.e. work would increase), in both comparisons, students in the VP sequence were more likely to respond that work would stay the same while students in the PV sequence were more likely to provide an alternate response (“other”).

The same trend emerged for the comparison of responses provided to Q6S after the first experiment. In Q6S, students were asked to explain how making the surface rougher would affect the inclined plane’s actual mechanical advantage (AMA). Students’ responses fell in the categories “AMA decreased”, “AMA stayed the same”, and “AMA increased”. While there was no difference between the numbers of students providing the physically correct response (i.e. AMA would decrease), students in the VP sequence were more likely to respond that AMA would stay the same, while students in the PV sequence were more likely to respond that AMA would increase.

### *7.2.3 Summary and Discussion*

In the PWF09 study, students completed both physical and virtual experiments, but in different orders. In the PV sequence, students completed the physical experiment first, followed by the virtual experiment. In the virtual experiment, students completed the virtual experiment, followed by the physical experiment. Students answered analysis questions after each experiment.

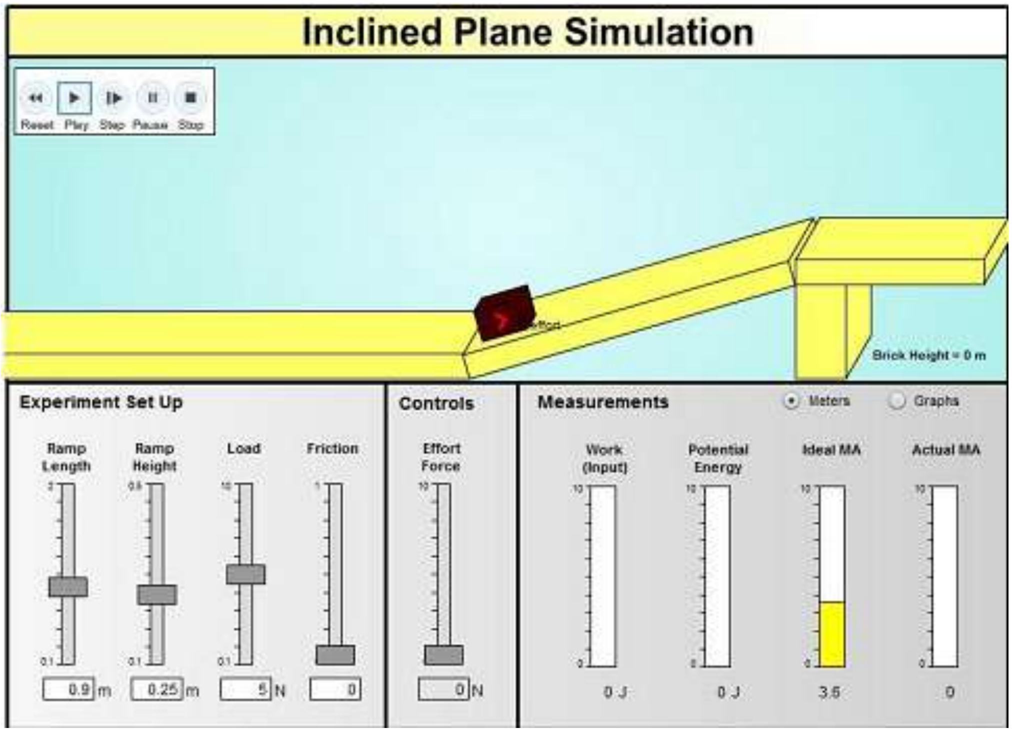
Many types of comparisons could be made. For clarity and relevance, I have focused on two specific comparisons. First, I compared the responses given in both sequences after performing the first experiment. Similar to the PWS09 study, this comparison addresses what students learn in the physical and virtual experiments. Second, I compared the responses given after the physical experiment in both sequences. This comparison addresses whether using the simulation before the physical experiment affects how students interpret the physical data. I believe this comparison is important because the goal of much of physics instruction is for students to make sense of the real world.

All three questions (Q1L, Q5L and Q6L) where students in the PV sequence gave more correct interpretations of the physical data than students in the VP sequence asked students to consider varying the length of the inclined plane. These questions asked students how increasing the length of the inclined plane affected the force needed to lift the load and ideal and actual mechanical advantage. It is interesting that this difference was significant only in the physical data comparison, and not for the comparison between the responses given after the first experiments, where students in the two sequences were looking at different data. It is possible that students are more aware of the length of the inclined plane in the physical experiment because they physically replace shorter boards with longer boards. Also, force and mechanical advantage can be "felt" in the physical experiment, which may help students understand the changes better than the simulation where force is displayed as a meter, or bar chart.

Examining students' data tables revealed that they often had difficulty making accurate force measurements in the physical experiment. For example, some students recorded the same value of applied force needed for inclined planes with the same length and different heights. This likely explains why students in the VP sequence more frequently provided the correct response to Q1H, which asked students to describe the relationship between ramp height and applied force, and Q5H, which asked students to describe the relationship between ramp height and ideal mechanical advantage. This suggests that students may need support to correctly use the spring scale to make force measurements. Another option is ensure that the change in force between two heights, two lengths or two surfaces is large enough to be detected even if students do not make careful measurements.

Across all three work and potential energy comparison questions, students in the VP sequence were more likely than students in the PV sequence to give responses about how work and potential energy related to each other. On the other hand, students in the PV sequence were more likely than students in the VP sequence to give responses that discussed work and potential energy separately. This difference can be explained by how the two environments support dynamic transfer, or the development of new ideas. In the simulation, work and potential energy were displayed side-by-side as bar charts, as shown in Figure 7.40 below. As discussed Section

2.5.2.4, one way an environment can support dynamic transfer is by providing a “focal point for coordination”. The bar graphs may help students construct ideas about how work and potential energy compare, leading students in the VP sequence to provide more productive responses. This idea is explored in more detail in Chapter 9. Importantly, the students in the VP sequence continued to provide these more productive responses when they performed the physical experiment, without the extra support from the environment.



Brick Height = 0 m

● Meters ○ Graphs

Ramp Length 0.9 m

Ramp Height 0.25 m

Load 5 N

Friction 0

Effort Force 0 N

Work (Input) 0 J

Potential Energy 0 J

Ideal MA 3.6

Actual MA 0

Figure 7.40 Inclined plane simulation for PWF09.

In the physical data comparisons, students in the VP sequence were more likely than students in the PV sequence to interpret the physical data to indicate that work was constant or nearly constant across machines and that work and potential energy were equal or nearly equal. This difference can be explained by Chinn and Brewer’s (1993) framework of possible responses to anomalous data. When data does not agree with an individual’s current theory, the individual can have one of several responses to the anomalous data: ignore the data; reject the data; exclude the data; hold the data in abeyance; reinterpret the data while maintaining the theory; make peripheral theory changes; or change the theory. Properties of the data may affect the stance one takes towards that data. For example, data that is not viewed as credible can be easily rejected, and ambiguous data can be easily reinterpreted

In the VP sequence, students have the opportunity to explore work and potential energy in a frictionless environment before encountering the physical experiment, where it is impossible to run a trial in the absence of friction. Thus, students first encounter data that is easily interpreted to indicate that the work needed to lift a load does not depend on length and that work and change in potential energy are equal in the absence of friction. Students then encounter ambiguous data in the physical experiment. Chinn and Brewer's framework suggests students may reinterpret the data from the physical experiment to fit the theory they developed from the virtual experiment. In addition, I provide evidence in Chapter 10 that students trust the simulation more than the physical experiment. Chinn and Brewer's framework suggests that students may reject the data from the physical experiment because they view it as less credible than the data from the physical experiment.

Students in the PV and VP sequences provided different types of non-physically correct responses to questions Q1S, Q2S and Q6S. Each of these questions asked students to explain how changing the surface of the inclined plane affected a physical quantity, including force, work and actual mechanical advantage (AMA). For each question, students in the VP sequence were more likely than students in the PV sequence to respond that the physical quantity (i.e. force, work or AMA) would not change. In the simulation, students change the surface by adjusting a slider for friction or typing in a number between zero and one (see Figure 7.40 above). The graphic of the surface changes to be covered with small dots to indicate a rough surface. It is possible that this change is not very salient for students. Thus, students may be less aware of the fact that they are changing the surface in the simulation than in the physical experiment.

These results indicate that students may gain a better sense of how changing length affects certain variables from the physical experiment. On the other hand, it may be beneficial to students' understanding of work and potential energy to complete the virtual experiment first.

## 7.3 Trends in Inclined Plane Worksheet Analysis

While there were differences between the designs of the PWS09 and PWF09 inclined plane studies, students in the PWS09 study performed a subset of the activities performed by students in the PWF09 study. Thus, it is still possible to look for trends across the two studies. The main trend that emerges is the difference in how students discuss work after completing the physical or virtual experiments. In both studies, students who used the simulation were more likely to observe that the work required to lift a load to a constant height does not depend on the length of inclined plane used. The different data encountered by students using physical or virtual manipulatives explains why the students who used the physical manipulative provided different responses about work. However, in both the PWS09 and PWF09 studies the students who used the simulation were more likely to make comparisons between work and potential energy, while the students who used the physical equipment were more likely to talk about work and potential energy separately. One possible explanation for this difference is that the simulation offers more support for dynamic transfer, or the construction of new ideas, than the physical equipment. This idea is further explored in Chapter 9.

In the PWF09 study, students who used the physical equipment first provided more correct responses about how length affected force and ideal and actual mechanical advantage. This result was not found in the PWS09 study. One difference between the two studies was that in Spring 2009, students performed separate activities about length, height and surface, whereas in Fall 2009 students performed one activity where they changed all three features. While students were provided with enough support to conduct properly designed trials (i.e. to only change one variable at a time), it is possible that students had more difficulty drawing interpretations when several independent factors had been manipulated in the same data table. Several examples of students drawing incorrect conclusions from correct data tables were provided above.

Overall, the inclined plane studies provide evidence that students’ understanding of work and potential energy may be better supported by conducting the virtual experiment prior to the physical experiment. The simulation appears to help students better understand the physical experiment.

# CHAPTER 8 - Inclined Plane Studies: Test Analysis

In this chapter, I present the quantitative analysis of students' performance on the conceptual test used in the inclined plane studies. The two inclined plane implementations were quite different in terms of format, so the results from the two implementations are discussed separately. In Inclined Plane Study #1: PWS09, each student completed only a subset of the activities performed in Inclined Plane Study #2: PWF09. In the PWS09 study, each student used only the physical equipment or computer simulation and performed activities about length and height or length and friction. In the PWF09 study, students used both the physical and virtual manipulatives and performed activities about length, height and friction. The results from the conceptual test help address Research Question 1, specifically the questions:

- What do students learn from the physical activities, and what do they learn from the virtual activities?
- When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity?
- When students do both physical and virtual activities, does one sequence lead to better conceptual understanding than the other?

I performed the statistical analysis for the PWS09 studying using SPSS. The statistical analysis for the PWF09 study was conducted with the assistance of Dr. Leigh Murray and Zhining Ou of the Kansas State University Statistics Department. Refer to Section 3.4.4 for a description of the analysis procedures used for each study.

## 8.1 Inclined Plane Study #1: Physical World Spring 2009 (PWS09)

For this analysis, students' test scores were calculated from the sixteen multiple-choice questions on the test used in the PWS09 study. These questions were described in Table 4.13 in Section 4.3.1.3, and the test is included in Appendix N. We performed analyses on the total score as well as concept sub-scores for force (six questions), work/energy (seven questions), and mechanical advantage (three questions).

The PWS09 Inclined Plane study involved four treatments. Students in two treatments used the physical equipment; one treatment performed activities about changing the length and height of the inclined plane (LH Physical), while the other performed activities about changing the length and surface (friction) of the inclined plane (LF Physical). The other two treatments used the computer simulation. Again, students either performed activities about length and height (LH Virtual) or length and friction (LF Virtual).

For the statistical analysis, I used an ANCOVA to analyze students' performance on the inclined plane conceptual test in the four conditions. The pre-test score was used as a covariate, and the treatment was used as a fixed factor. For cases where treatment was a significant predictor of post-test score, post-hoc contrasts were explored to identify which groups exhibited the statistical difference. The total score and force, work and mechanical advantage sub-scores were each analyzed. These results help to address whether the physical or virtual manipulative offers better support for students' learning.

### *8.1.1 Total Score*

Figures 8.1 below displays the pre-test and post-test results for total score for the four treatments. Students could earn up to a maximum of 16 points for the total score, one point for each multiple-choice question. As shown in Figure 8.1 below, the four conditions began with similar mean total pre-test scores (LH $\text{Physical}_{\text{pre}}$=9.7, S.E.=0.4; LH $\text{Virtual}_{\text{pre}}$=9.6, S.E.=0.4; LF $\text{Physical}_{\text{pre}}$=9.6, S.E.=0.3; LF $\text{Virtual}_{\text{pre}}$=9.1, S.E.=0.4). The LF Virtual pre-test score was slightly lower than that of the other conditions. After performing the activities, students in the LH Virtual condition scored higher than students in the other conditions (LH $\text{Physical}_{\text{post}}$=10.6, S.E.=0.3; LH $\text{Virtual}_{\text{post}}$=12.4, S.E.=0.4; LF $\text{Physical}_{\text{post}}$=10.6, S.E.=0.2; LF $\text{Virtual}_{\text{post}}$=10.7, S.E.=0.4). The other three conditions had similar mean total post-test scores.

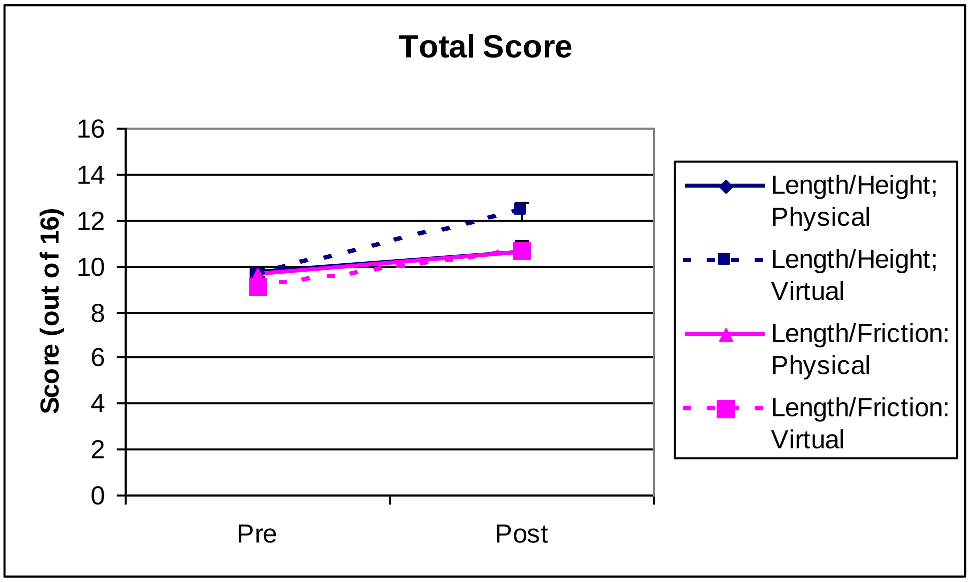


**Figure 8.1 Physical World Spring 2009 Inclined Plane Test Scores: Total.**

The covariate pre-test total score was significantly related to the post-test total score, *F*(1, 144)=35.4, p<.001. There was also a significant effect of treatment on the post-test total score, *F*(3, 144)=8.4, p<.001. Planned contrasts revealed students in the LH virtual condition scored significantly higher on the post-test than students in the other three conditions (LH Virtual/LH Physical: p<.001; LH Virtual/LF Physical: p<.001; LH Virtual/LF Virtual: p=.002). There was no significant difference between the post-test total scores in the LH Physical, LF Physical and LF Virtual conditions (LH Physical/LF Physical: p=.993; LH Physical/LF Virtual: p=.457; LF Physical/LF Virtual: p=.386). This indicates that students were most successful on the post-test if they performed the length and height activities in the simulation. Students in the other three conditions performed equally on the post-test. The force, work/energy and mechanical advantage sub-scores are analyzed below to explore if a particular concept or concepts led to this difference.

### *8.1.2 Force Sub-score*

Figure 8.2 below displays the pre-test and post-test means for the force sub-score for the four treatments. Students could earn up to a maximum of six points for the force sub-score, one point for each multiple-choice question related to force. The mean pre-test and post-test force sub-scores were similar in the four conditions. The LF physical condition began with a slightly higher mean pre-test force sub-score than the others (LH Physical$_{pre}$=4.2, S.E.=0.3; LH Virtual$_{pre}$=3.8, S.E.=0.2; LF Physical$_{pre}$=4.4, S.E.=0.2; LF Virtual$_{pre}$=3.9, S.E.=0.2), while the LF physical condition ended with a slightly higher post-test score (LH Physical$_{post}$=5.4, S.E.=0.1; LH Virtual$_{post}$=5.2, S.E.=0.2; LF Physical$_{post}$=5.2, S.E.=0.1; LF Virtual$_{post}$=5.0, S.E.=0.1).

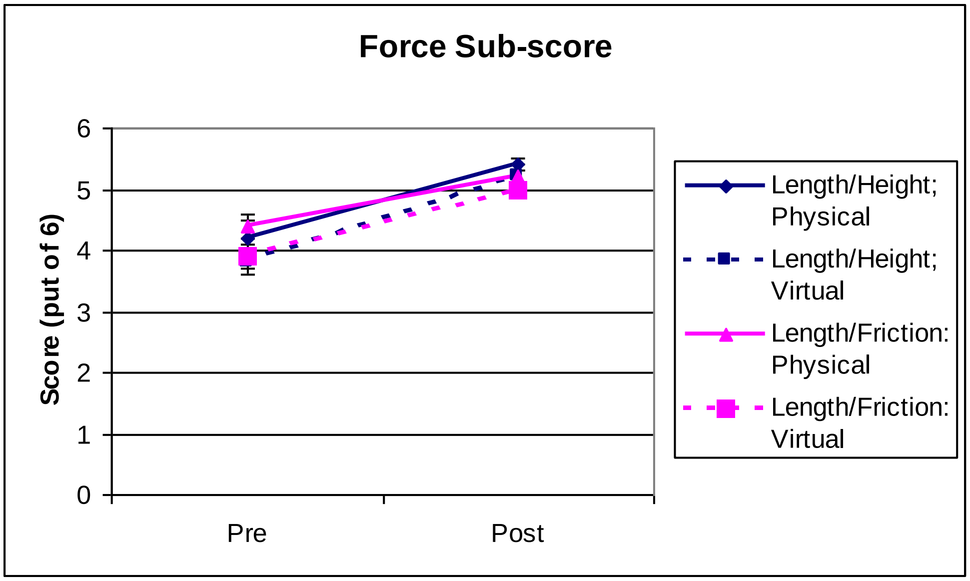


**Figure 8.2 Physical World Spring 2009 Inclined Plane Test Scores: Force Sub-score.**

The covariate pre-test score was significantly related to the post-test force sub-score, *F*(1, 144)=8.9, p=.003. Treatment was not significantly related to the post-test score, *F*(3, 144)=0.9, p=.458. This indicates that the four conditions equally supported students' learning about force.

This result is potentially surprising. The physical experiment provides students with the kinesthetic experience of applying the force to move the load. One might expect that the physical experience would help students develop a better understanding of force. However, as gauged by the conceptual test, the physical and virtual manipulatives and length/height and length/friction experiments provided equal support for students' understanding of force. It is possible that these students can successfully learn about force from the simulation because they already have real life experience with force and inclined planes. We may expect that less mature students (i.e. middle school students) would experience more difficulty with learning about force from the simulation. It is also possible that the physical manipulative is in fact benefiting the students more than the virtual manipulative, but in a way that is not captured by the conceptual test.

### *8.1.3 Work/energy Sub-score*

Figure 8.3 below displays the pre-test and post-test means for the force sub-score for the four treatments. Students could earn up to a maximum of seven points for the work/energy sub-score, one point for each question related to work or potential energy. The four conditions began with similar mean work/energy pre-test sub-scores (LH $\text{Physical}_{\text{pre}}$=3.9, S.E.=0.2; LH $\text{Virtual}_{\text{pre}}$=4.2, S.E.=0.2; LF $\text{Physical}_{\text{pre}}$=3.7, S.E.=0.2; LF $\text{Virtual}_{\text{pre}}$=3.9, S.E.=0.2). However, there was a bigger spread among the post-test scores. Students in the LH virtual had the highest scores, while students in the LH physical condition had the lowest scores (LH $\text{Physical}_{\text{post}}$=3.2, S.E.=0.2; LH $\text{Virtual}_{\text{post}}$=5.0, S.E.=0.3; LF $\text{Physical}_{\text{post}}$=3.6, S.E.=0.1; LF $\text{Virtual}_{\text{post}}$=4.0 S.E.=0.2).

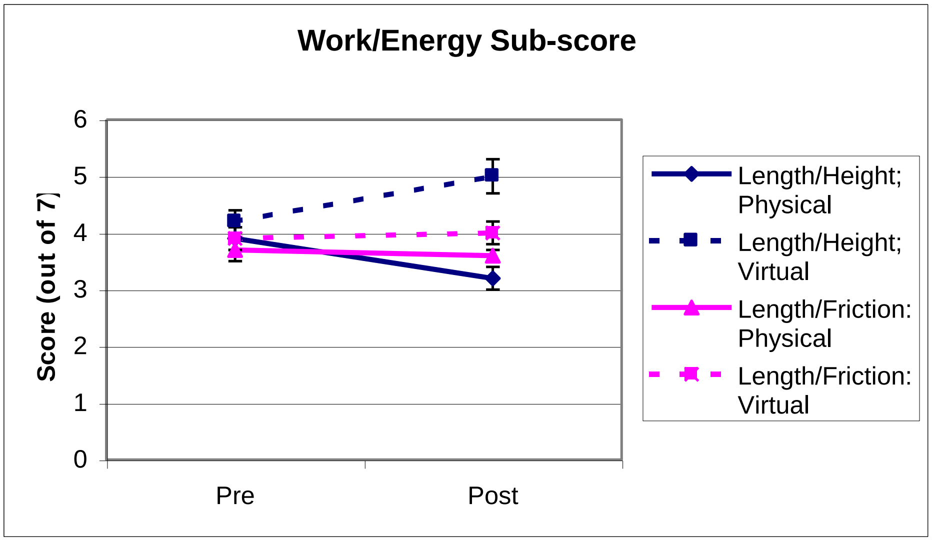


**Figure 8.3 Physical World Spring 2009 Inclined Plane Test Scores: Work/energy.**

The covariate pre-test work/energy sub-score was significantly related to the post-test score, *F*(1, 144)=28.7, p<.001. There was also a significant effect of treatment on the post-test work/energy sub-score, *F*(3, 144)=12.3, p<.001. Planned contrasts revealed that students in the LH Virtual condition scored significantly higher on the post-test than students in the other three conditions (LH Virtual/LH Physical: p<.001; LH Virtual/LF Physical: p<.001; LH Virtual/LF

Virtual: p=.004). In addition, students in the LF Virtual condition scored significantly higher than students in the LH Physical condition (p=.010). There was no significant difference in the post-test work/energy sub-scores between the LH Physical and LF Physical conditions (p=.120) and the LF Physical and LF Virtual conditions (p=166). This indicates that students were most successful on the work/energy questions on the post-test if they performed the length and height activities in the simulation.

These results seem to indicate that students had more difficulty answering the conceptual test questions about work if they had any experience with friction during the activities. Students in the Length/Height Physical group were least likely to have the learning experiences necessary to answer questions about work in a frictionless environment, like those on the conceptual test, because they only performed experiments with one type of surface, which had some friction. Thus, they observed that longer ramps required more work to lift a load than did shorter ramps and that work required to lift the load was greater than the change in the load's potential energy. Students in the Length/Friction Physical and Virtual groups had explicit experience with varying friction, which was intended to help students reason about the ideal (i.e. frictionless) case. In fact, students in the Length/Friction Virtual group observed frictionless trials in both the length and friction activities. However, the results indicate that these experiences did not lead to as much success on the test as the length and height virtual activities. Students in the Length/Height Virtual group never observed the effects of friction and had the highest scores on the work/energy questions. Yet, it is our goal that students understand work both in the presence and the absence of friction. This indicates students need additional support to differentiate between real world (i.e. with friction) and ideal (i.e. frictionless) conditions.

### *8.1.4 Mechanical Advantage Sub-score*

Figure 8.4 below displays the pre-test and post-test means for the mechanical advantage sub-score for the four treatments. Students could earn up to a maximum of three points for the mechanical advantage sub-score, one point for each multiple-choice question related to mechanical advantage. The four conditions exhibited similar pre-test means on the mechanical advantage sub-score (LH $\text{Physical}_{\text{pre}}$=1.6, S.E.=0.2; LH $\text{Virtual}_{\text{pre}}$=1.5, S.E.=0.2; LF $\text{Physical}_{\text{pre}}$=1.5, S.E.=0.1; LF $\text{Virtual}_{\text{pre}}$=1.3, S.E.=0.2). At the post-test, the mean scores were again quite similar (LH $\text{Physical}_{post}$=2.0, S.E.=0.2; LH $\text{Virtual}_{post}$=2.1, S.E.=0.2; LF $\text{Physical}_{post}$=1.7, S.E.=0.1; LF $\text{Virtual}_{post}$=1.7, S.E.=0.2).

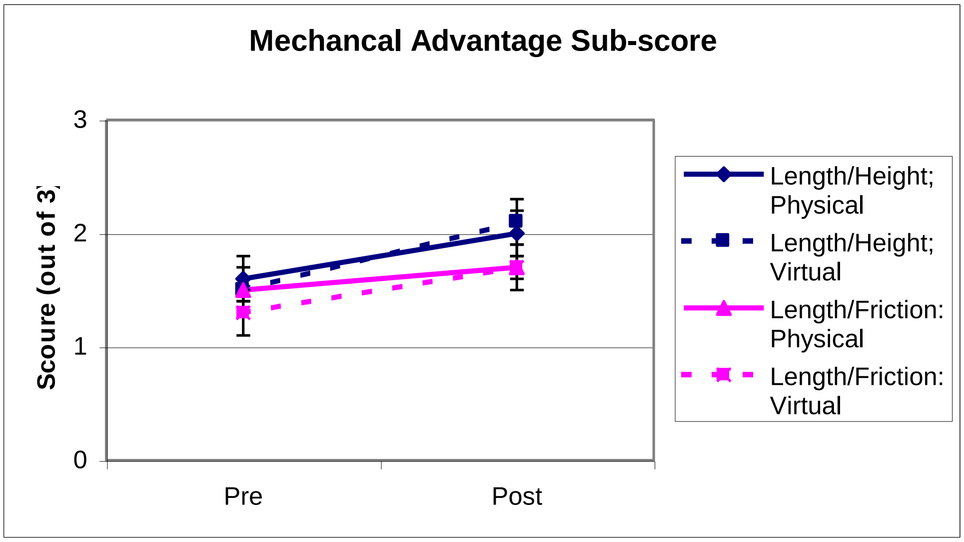


**Figure 8.4 Physical World Spring 2009 Inclined Plane Test Scores: Mechanical Advantage.**

The covariate pre-test mechanical advantage sub-score was significantly related to the post-score, *F*(1, 144)=19.5, p<.001. Treatment was not significantly related to post-test score, *F*(3, 144)=1.6, p<.195. This indicates that all four conditions equally supported students' learning about mechanical advantage.

This result is not necessarily surprising, as mechanical advantage can be thought of as a hybrid between a concept that can be physically experienced, like force, and a more abstract concept, like potential energy. Since mechanical advantage is closely related to force, one might expect the physical experiment to provide better support for students' learning about mechanical advantage since they can kinesthetically experience which inclined plane is making it easier to move the load. However, mechanical advantage is also an abstract concept, in that it is found numerically by dividing the load's weight by the force needed to lift it. One might expect the simulation to better help students understand abstract concepts because it performs calculations and displays results in multiple representations (both numerically and as a bar chart). The result that all four conditions offered equal support for students understanding might indicate that the possible benefits of the physical and virtual manipulatives balanced. In addition, since the mean scores increased by less than one question, it is possible that none of the conditions offered much support for students' understanding of mechanical advantage.

### *8.1.5 Summary of Results*

Students in the PWS09 inclined plane study performed one of four sets of activities: physical or virtual experiments about length and height, or physical or virtual experiments about length and surface (friction). The ANCOVA analysis results are summarized in Table 8.1 below; refer to the discussion above for contrasts between the conditions. The analysis indicates that all four treatments provided equal support for students' learning about force and mechanical advantage. However, the Length/Height Virtual activity appears to have offered more support for the total score and work/energy sub-scores. In addition, the LF Virtual condition offered more support for students' learning about work and energy than did the LH Physical condition.

**Table 8.1 Physical World Spring 2009 Test Analysis Summary**

| | **Effect** | **F** | **p** |
|---|---|---|---|
| **Total** | *Pretest* | $F(1, 144)= 35.4$ | <.001 |
| | *Manipulatives* | $F(3, 144)= 8.4$ | <.001 |
| **Force** | *Pretest* | $F(1, 144)= 8.9$ | .003 |
| | *Manipulatives* | $F(3, 144)= 0.9$ | .458 |
| **Work/Energy** | *Pretest* | $F(1, 144)= 28.7$ | <.001 |
| | *Manipulatives* | $F(3, 144)= 43.3$ | <.001 |
| **MA** | *Pretest* | $F(1, 144)= 19.5$ | <.001 |
| | *Manipulatives* | $F(3, 144)= 1.6$ | .195 |

It appears that students in the LH Virtual group had higher total scores because they performed better on the questions about work and potential energy. This group of students never observed the effects of friction because both the length and height inclined plane simulations were frictionless. Students in the LF Virtual group also observed frictionless trials in both the length and height experiments, but it appears that observing even one trial with friction decreased the likelihood that students would correctly respond to questions about work in ideal (i.e. frictionless) conditions. This suggests students need additional support to differentiate between real world (i.e. with friction) and ideal (i.e. frictionless) conditions.

In addition, this study does not find support for the idea that kinesthetic experiences benefit students' learning about concepts that can be directly sensed or observed, such as force.

There are several possible explanations for this result. These students may have enough prior experience with force and inclined planes to learn about force successfully from the simulation. It is possible that students with less background knowledge, such as middle school students, may have more difficulty learning from the simulation. It is also possible that the physical experiment does benefit students' understanding of force more than the simulation, but it a way that is not measured by the conceptual test.

## 8.2 Inclined Plane Study #2: PWF09

For this analysis, students' test scores were calculated from the eighteen multiple-choice questions on the test used in the PWF09 study. These questions were described in Table 4.16 in Section 4.3.2.3, and the test is included in Appendix P. We performed analyses on the overall score, as well as concept sub-scores for force (six questions), work/energy (nine questions), and mechanical advantage (three questions).

The PWF09 Inclined Plane study involved two treatments. All students used both physical and virtual manipulative to experiment with the length, height and surface of the inclined plane. However, some students used the manipulatives in the physical-virtual (PV) sequence, while other students used the manipulatives in the virtual-physical (VP) sequence.

A mixed ANOVA was used to analyze students' performance in the PV and VP sequences. Laboratory section and treatment were used as between-subjects factors, and test score (at the levels pre-test, mid-test and post-test) was used as a within-subjects factor. The total score and force, work and mechanical advantage sub-scores were each analyzed. The main effect ("Test") explains whether scores changed among pre-test, mid-test and post-test, regardless of treatment. The interaction effect ("Test*Trt") explains whether the way students' scores changed depended on the sequence in which they performed the physical and virtual experiments.

### *8.2.1 Total Score*

Figure 8.5 below displays the pre-test, mid-test and post-test results for the overall score for students in the physical-virtual (PV) and virtual-physical (VP) sequences. Students could earn up to a maximum of eighteen points for the total score, one point for each multiple-choice question. The mean pre-test total scores for both sequences were very similar ($PV_{pre}$=11.8, S.E.=0.4; $VP_{pre}$=11.7, S.E.=0.5). Students completed the mid-test after they had performed the first set of activities. In the PV sequence, the mid-test was taken after students completed the physical activity, and in the VP sequence the mid-test was taken after students completed the virtual activity. The mean mid-test total score was slightly higher in the VP sequence than in the PV sequence ($PV_{mid}$=13.2, S.E.=0.4; $VP_{mid}$=14.0, S.E.=0.5). Students completed the post-test after performing both sets of activities. The mean post-test total scores for both sequences were very similar ($PV_{post}$=14.0, S.E.=0.4; $VP_{post}$=14.0, S.E.=0.5). In the PV sequence, the mean total score increased from pre-test to mid-test to post-test. On the other hand, in the VP sequence, the mean total score increased from pre-test to mid-test and then stayed the same from mid-test to post-test.

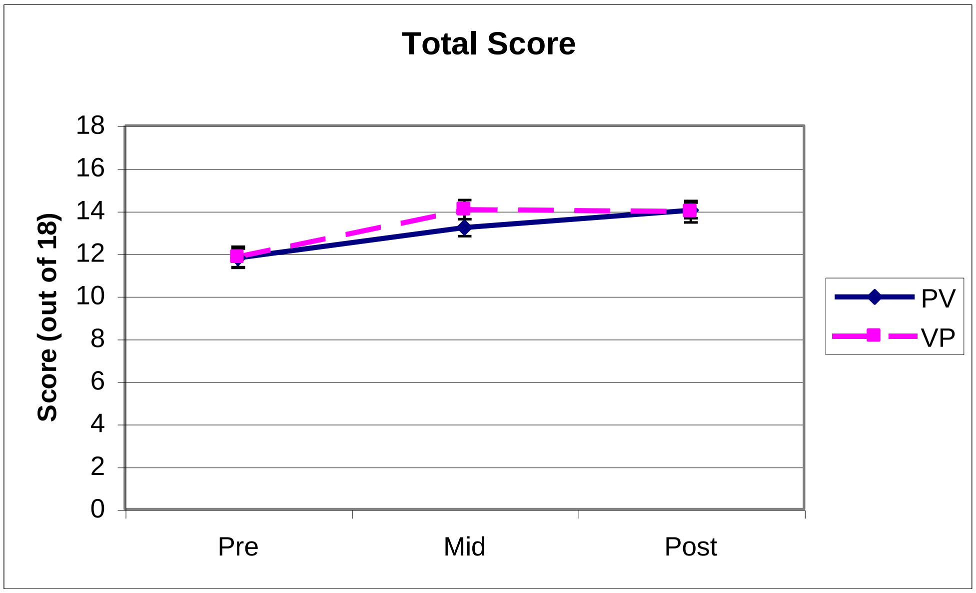


**Figure 8.5 Physical World Fall 2009 Inclined Plane Test Scores: Total.**

The pre-test, mid-test and post-test total score means are shown in Figure 8.5 above. The main effect of treatment was significant, *F*(2, 214)=37.8, p<.001. The planned contrasts revealed students' scores changed significantly from pre-test to mid-test, *F*(1, 214)=46.2, p<.001, r=.42, and pre-test to post-test *F*(1, 214)=65.6, p<.001, r=.48. However, scores did not change significantly from mid-test to post-test, *F*(1, 214)=1.7, p=.194, r=.09. This indicates students learned about the physics of inclined planes from the first activity, but did not learn additional concepts from the second activity. The interaction effect was not significant, *F*(2, 214)=1.77, p=.173. This means students' scores did not change differently in the PV and VP sequences, and indicates students learned the same amount from the physical and virtual activities. Below, I discuss the analysis of the force, work/energy and mechanical advantage sub-scores to explore whether the physical and virtual manipulatives and PV and VP sequences offered equal support for the specific concepts as well as the total score.

### *8.2.2 Force Sub-score*

Figure 8.6 below displays the mean pre-test, mid-test and post-test force sub-scores for the PV and VP sequences. Students could earn up to a maximum of six points for the force sub-score, one point for each multiple-choice question related to force. Students in the PV sequence began with a slightly higher mean pre-test force score than students in the VP sequence ($PV_{pre}$=4.6, S.E.=0.2; $VP_{pre}$=4.2, S.E.=0.2). At the mid-test, however, the mean score was nearly equal for the two sequences ($PV_{mid}$=5.0, S.E.=0.2; $VP_{mid}$=5.1, S.E.=0.2). At the post-test, students in the PV sequence slightly outperformed students in the VP sequence ($PV_{post}$=5.5, S.E.=0.2; $VP_{post}$=5.1, S.E.=0.2).

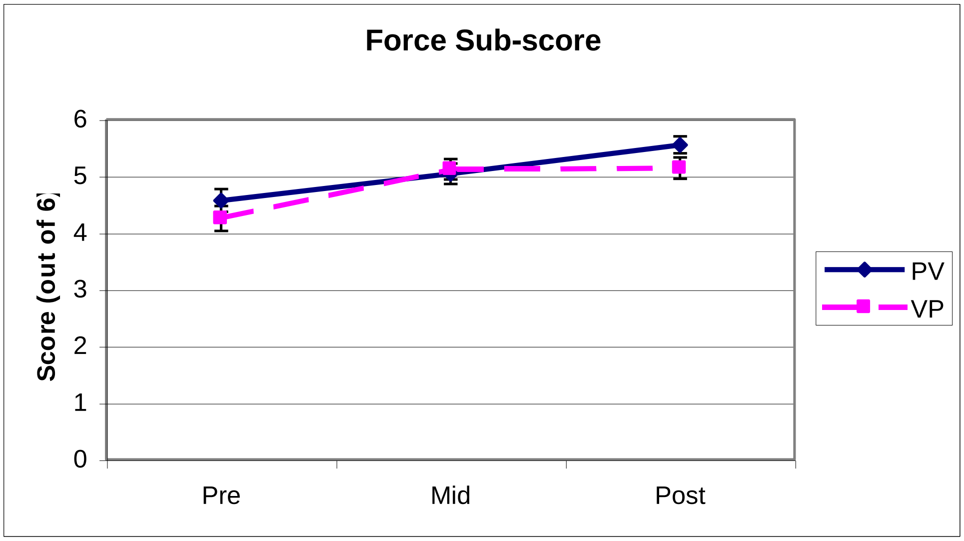


**Figure 8.6 Physical World Fall 2009 Inclined Plane Test Scores: Force.**

The main effect of treatment was significant, *F*(2, 214)=22.1, p<.001. The planned contrasts revealed students' scores changed significantly from pre-test to mid-test, *F*(1, 214)=21.2, p<.001, r=.30, and pre-test to post-test *F*(1, 214)=41.0, p<.001, r=.40. However, scores did not change significantly from mid-test to post-test, *F*(1, 214)=3.2, p=.214, r=.12. This indicates students learned about force in the first activity, but did not continue to learn about force in the second activity in both sequences. The interaction effect was not significant, *F*(2, 214)=1.62, p=.200. This means students' scores did not change differently in the PV and VP sequences and indicates the physical and virtual manipulatives offered equal support for students' learning about force.

This result is somewhat surprising. Since the physical manipulative provides students with a kinesthetic experience with force, one may expect the physical manipulative to better support students' learning about this concept than the virtual manipulative. However, the results indicate the physical and virtual manipulative equally supported students' learning about force. It is possible that students bring prior knowledge of force in the context of inclined planes from the real world to the activities and do not experience much difficulty this concept. In both sequences, the post-test force sub-score mean is very close to the maximum score, supporting the idea that students do not have difficulty learning about force in the context of inclined planes. It is possible that students' with less prior knowledge may benefit more from performing the activity with the physical manipulative, but that experience does not appear to be necessary for college age students.

### *8.2.3 Work/energy Sub-score*

Figure 8.7 below displays the mean pre-test, mid-test and post-test work/energy sub-scores for the PV and VP sequences. Students could earn up to a maximum of nine points for the work/energy sub-score, one point for each multiple-choice question related to work or potential energy. The two sequences had similar mean work/energy scores at the pre-test ($PV_{pre}$=5.2, S.E.=0.3; $VP_{pre}$=5.4, S.E.=0.3). At the mid-test, the mean work/energy score had increased more in the VP sequence than in the PV sequence ($PV_{mid}$=5.6, S.E.=0.3; $VP_{mid}$=6.4, S.E.=0.3). At the post-test, students in the VP sequence continued to outperform students in the PV sequence ($PV_{post}$=5.8, S.E.=0.3; $VP_{post}$=6.3, S.E.=0.3).

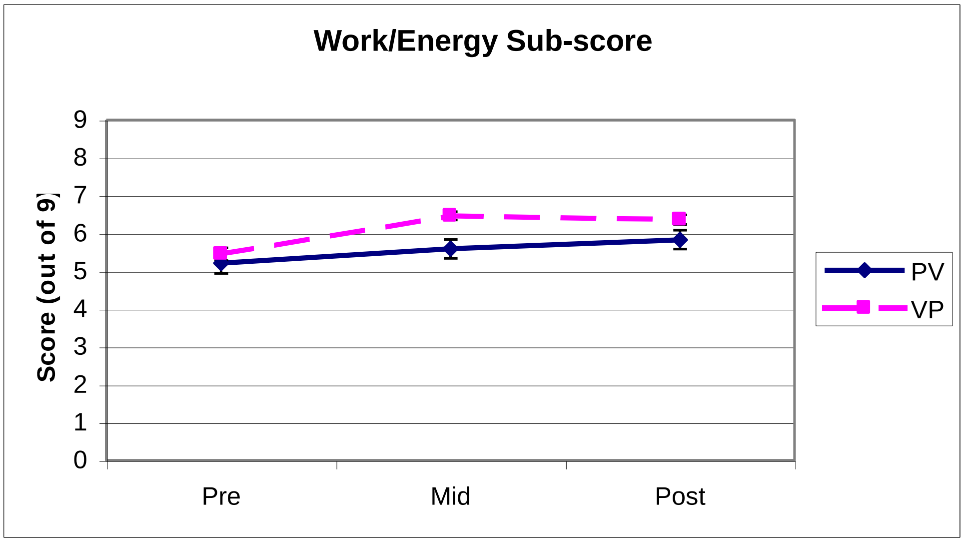


**Figure 8.7 Physical World Fall 2009 Inclined Plane Test Scores: Work/energy.**

The main effect of treatment was significant, *F*(2, 214)=15.7, p<.001. The planned contrasts revealed students' scores changed significantly from pre-test to mid-test, *F*(1, 214)=21.2, p<.001, r=.30, and pre-test to post-test *F*(1, 214)=26.0, p<.001, r=.33. However, scores did not change significantly from mid-test to post-test, *F*(1, 214)=0.3, p=1.0, r=.04. This indicates students learned about work and potential energy in the first activity, but did not continue to learn about work and potential energy in the second activity in both sequences. The interaction effect was not significant, *F*(2, 214)=2.24, p=.109. This means students' scores did not change differently in the PV and VP sequences and indicates the physical and virtual manipulatives offered equal support for students' learning about work and potential energy.

It is surprising that the physical and virtual manipulatives provided equal support for students' learning about work in the context of inclined planes. Since work is an abstract concept and requires calculation, it seemed likely that the simulation would improve students' understanding of work more than the physical experiment. In the simulation, students are presented with data from ideal (i.e. frictionless) conditions, making the relationships between length and work and work and potential energy in ideal conditions more transparent than in the physical experiment. Since many of the conceptual test questions asked about ideal conditions, it is surprising that students performance on those questions did not vary between the PV and VP sequences. One possible explanation for this result is that, even in the simulation, students performed at least one trial where they observed the effects of friction. It is possible that the results of the trial with friction better fit students' expectations about work from their everyday lives, and thus were what students relied on when they were answering the test questions.

### *8.2.4 Mechanical Advantage Sub-score*

Figure 8.8 below displays the mean pre-test, mid-test and post-test scores for the mechanical advantage sub-score for the PV and VP sequences. Students could earn up to a maximum of three points for the mechanical advantage sub-score, one point for each question related to mechanical advantage. The mean mechanical advantage scores were very similar for the two sequences. At the pre-test, the sequences had almost identical scores ($PV_{pre}$=2.0, S.E.=0.2; $VP_{pre}$=2.1, S.E.=0.2). The mean scores for both sequences increased similarly from pre-test to post-test ($PV_{mid}$=2.6, S.E.=0.1; $VP_{mid}$=2.5, S.E.=0.1). The mean scores stayed consistent from mid-test to post-test for both sequences ($PV_{post}$=2.6, S.E.=0.1; $VP_{post}$=2.5, S.E.=0.1).

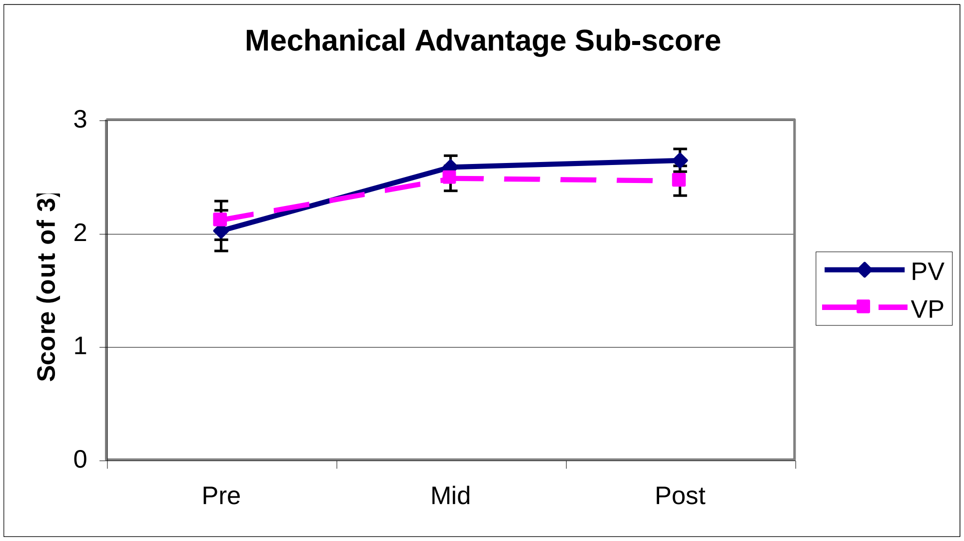


**Figure 8.8 Physical World Fall 2009 Inclined Plane Test Scores: Mechanical Advantage.**

The main effect of treatment was significant, *F*(2, 214)=18.1, p<.001. The planned contrasts revealed students' scores changed significantly from pre-test to mid-test, *F*(1, 214)=26.0, p<.001, r=.33, and pre-test to post-test *F*(1, 214)=28.1, p<.001, r=.34. However, scores did not change significantly from mid-test to post-test, *F*(1, 214)=0.04, p=1.0, r=.01. This indicates students learned about mechanical advantage in the first activity, but did not continue to learn about mechanical advantage in the second activity in both sequences. The interaction effect was not significant, *F*(2, 214)=1.32, p=.270. This means students' scores did not change differently in the PV and VP sequences and indicates the physical and virtual manipulatives offered equal support for students' learning about mechanical advantage.

It is not necessarily surprising that the physical and virtual manipulatives offered equal support for students' understanding of mechanical advantage. Arguments can be made in favor of both the physical and virtual manipulatives in the case of mechanical advantage. For example, mechanical advantage is closely related to the applied force needed to lift the load, which the physical experiment allows students to physically experience. However, mechanical advantage is a more abstract concept than force since it is based on a calculation, and the simulation, which its ideal (i.e. frictionless) conditions and multiple representations (i.e. numerical results and bar charts) may better help students learn abstract concepts. Since neither manipulative supported students' learning about mechanical advantage more than the other, it is possible that the advantages of each balanced. Also, since the mean score increased less than one point in both sequences, it is possible that neither manipulative offered much support for students' learning about mechanical advantage.

### *8.2.5 Summary of Results*

Students in the PWF09 inclined plane study performed both physical and virtual activities, but in different sequences. This study design allows for exploration of the comparative effectiveness of the physical and virtual experiments, the added benefit of performing both types of experiments, and the comparative effectiveness of the physical-virtual and virtual-physical sequences. A summary of the results of the mixed ANOVA is shown in Table 8.2 below.

**Table 8.2 Physical World Fall 2009 Test Analysis Summary**

| **Score** | | **F-test** | | **Pre/Mid Contrast** | | **Mid/Post Contrast** | | **Pre/Post Contrast** | |
|---|---|---|---|---|---|---|---|---|---|
| | **Effect** | ***F*** | **p** | ***F*** | **p** | ***F*** | **p** | ***F*** | **p** |
| **Total** | **Test** | *F*(2, 214)= 37.8 | <.001 | *F*(1, 214) =46.2 | <.001 | *F*(1, 214) =1.7 | .194 | *F*(1, 214) =65.6 | <.001 |
| | **Test* Treat** | *F*(2, 214)= 1.77 | .173 | | | | | | |
| **Force** | **Test** | *F*(2, 214)= 22.1 | <.001 | *F*(1, 214) =21.2 | <.001 | *F*(1, 214) =3.2 | .214 | *F*(1, 214) =41.0 | <.001 |
| | **Test* Treat** | *F*(2, 214)= 1.62 | .200 | | | | | | |
| **WE** | **Test** | *F*(2, 214)= 15.7 | <.001 | *F*(1, 214) =21.2 | <.001 | *F*(1, 214) =0.3 | 1.0 | *F*(1, 214) =26.0 | <.001 |
| | **Test* Treat** | *F*(2, 214)= 2.24 | .109 | | | | | | |
| **MA** | **Test** | *F*(2, 214)= 18.1 | <.001 | *F*(1, 214) =26.0 | <.001 | *F*(1, 214) <0.1 | 1.0 | *F*(1, 214) =28.1 | <.001 |
| | **Test* Treat** | *F*(2, 214)= 1.3 | .270 | | | | | | |

The results indicate that students learned only in the first experiment, whether it was physical or virtual, for the total score and the force, work/energy and mechanical advantage sub-scores. Students' scores did improve significantly from mid-test to post-test, as indicated by the non-significant main effect (Test) mid-test/post-test contrast for each score, which suggests their conceptual understanding as measured by the multiple choice test did not improve as a result of repeating the activity with the other manipulative type. In addition, the results indicate that students' learning was supported equally by the physical and virtual manipulative and PV and VP sequences on the total score and each sub-score, as the interaction effect (Treat*Test) was not significant for any of the scores.

This study does not find support for the idea that experimentation with physical and virtual manipulatives may provide different levels of support for students' understanding of specific concepts. While one may have expected the physical manipulative to provide better support for students' understanding of force than the virtual manipulative, students who used either manipulative performed similarly on the conceptual test. Students in both the PV and VP sequences performed well on the force questions, which suggests students did not have much difficulty learning this concept, possibly because they have prior experience with the force in the context of inclined planes from the real world. It is possible that students with less prior experience may benefit more from the physical manipulative. In addition, while one may have expected the virtual manipulative to provide more support for students' understanding of work and potential energy than the physical manipulative, students in both sequences again performed similarly on the work/energy questions on the conceptual test. It is possible that the trial with friction in the virtual experiment was more salient with students than the trials without friction, leading them to perform similarly to the students who had used the physical equipment. This suggests students may need additional support to differentiate work in conditions with and without friction.

## 8.3 Trends in the Inclined Plane Test Analysis

While there were differences between the designs of the PWS09 and PWF09 inclined plane studies, students in the PWS09 study performed a subset of the activities performed by students in the PWF09 study. Thus, it is still possible to look for trends across the two studies. In both studies, all conditions offered equal support for students' learning about force and mechanical advantage. However, in the PWS09 study, the Length/Height Virtual condition offered better support for total score and the work/energy sub-score, while both manipulatives and both sequences in the PWF09 study offered the same support for total score and the work/energy sub-score.

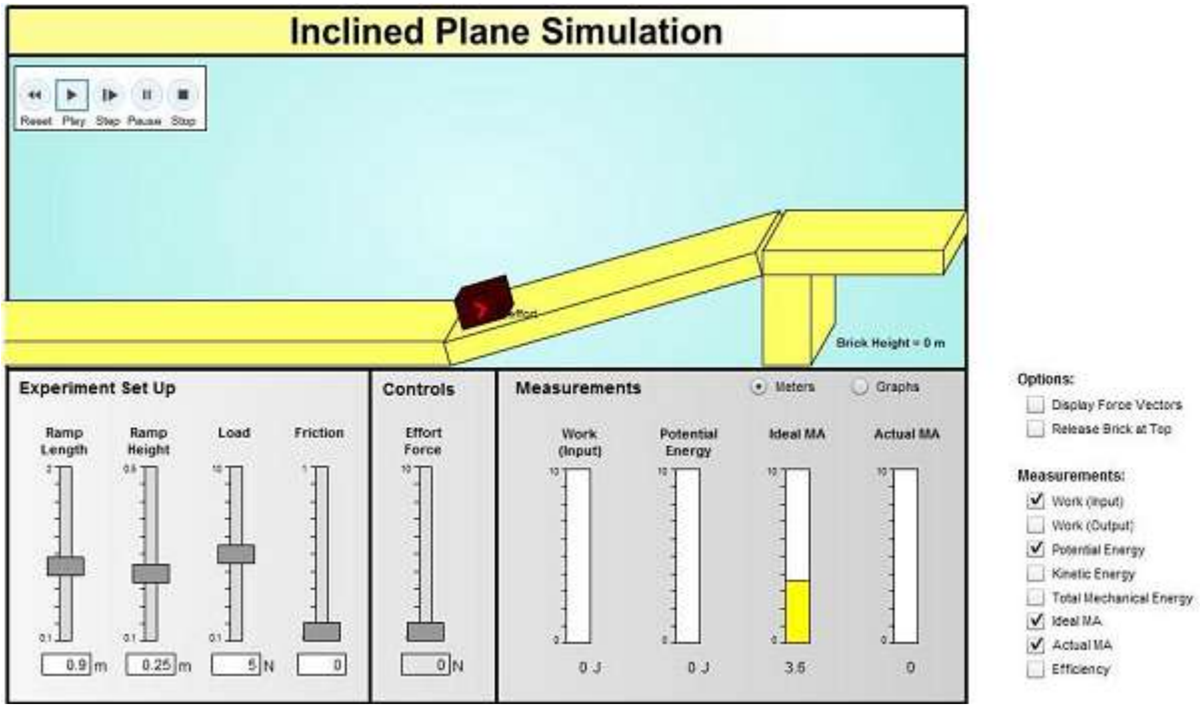
One possible explanation for the difference between the two studies is that students in the Length/Height Virtual condition of the PWS09 study never observed trials with friction, while students in the PWF09 study performed a trial with friction in the simulation. The simulations used for the length and height experiments in the PWS09 study only had frictionless ramps. Without friction, the work needed to lift a load is exactly equal to the change in the object's potential energy, which depends only on the mass of the object and the height to which it is lifted. With friction, however, more work is needed as some energy is dissipated to heat. In the presence of friction, the work needed to lift the load increases with length because friction is acting over a longer distance and more energy is dissipated to heat. Students in the LH Virtual condition of the PWS09 study never saw these potentially conflicting results about how changing the length of the inclined plane affects the work needed to lift the load. This explanation is supported by the fact that the performance of students in the Length/Friction Virtual condition of the PWS09 was similar to the performance of students who used the physical equipment. It appears that when students completed experiments about length, height and friction in the PWF09 study, their performance was more similar to that of the students in Length/Friction Virtual condition than that of the students in the Length/Height Virtual condition. This result seems to indicate that students have difficulty distinguishing between behavior in conditions with and without friction and should be provided with more scaffolding to explore this distinction.

# CHAPTER 9 - Dynamic Transfer Analysis

## 9.1 Introduction

In this chapter, I describe how the physical and virtual environments created by the physical equipment and simulation provided support for dynamic transfer. Dynamic transfer, as described by Schwartz *et al.* (2008) and summarized in Section 2.5.2.4, involves the coordination of component skills and ideas to develop new concepts. In other words, dynamic transfer is the process through which students construct new concepts. Schwartz *et al.* (2008). explain that the environment can support dynamic transfer in several ways: by allowing for distributed memory, by providing alternative interpretations and feedback, by serving as a candidate structure, and by providing a focal point for coordination. The way in which each environment provided or failed to provide each of these types of support are described in the following sections. It is important to note that the ways an environment can support dynamic transfer are closely linked to successful scaffolding.

This analysis is based on teaching/learning interviews conducted in Inclined Plane Study #3, described in Section 4.3.3. To review, two-hour interviews were conducted with eleven students. Five students used the physical inclined plane equipment, which consisted of: four lengths of ramps; a brick to create different heights of inclined planes; wood, wax paper and sandpaper surfaces; a block and masses to create different loads; a spring scale to measure force; a calculator; and paper for taking notes. Six students used the inclined plane simulation, shown in Figure 9.1 below. Students created ramps by moving the sliders associated with length, height and friction and selected a load. They then raised the slider for force, and could view the resulting measurements of work (input), work (output), potential energy, kinetic energy, total mechanical energy, ideal mechanical advantage, actual mechanical advantage, and efficiency. Each interview was recorded and transcribed. The transcripts and videos were analyzed in tandem for examples of how each environment provided support for dynamic transfer. This analysis is descriptive in nature, and I looked for examples of the variety of ways each environment provided support for dynamic transfer. No attempt was made to obtain frequency counts of how often each type of support was observed as the sample size was too small for frequency counts to carry much meaning.



Ramp Length 0.9 m
Ramp Height 0.25 m
Load 5 N
Friction 0
Effort Force 0 N

● Meters ○ Graphs

Work (Input) 0 J
Potential Energy 0 J
Ideal MA 3.6
Actual MA 0

Options:
☐ Display Force Vectors
☐ Release Brick at Top

Measurements:
☑ Work (Input)
☐ Work (Output)
☑ Potential Energy
☐ Kinetic Energy
☐ Total Mechanical Energy
☑ Ideal MA
☑ Actual MA
☐ Efficiency

**Figure 9.1 Inclined plane simulation used in interviews.**

In the analysis for each type of support for dynamic transfer, I present episodes from the interviews that highlight the various ways each environment supported or failed to support dynamic transfer. I also consider whether the support offered in one environment could be recreated in the environment in which it was not observed. In this way, I judged the extent to which each environment is able to support dynamic transfer.

## 9.2 Distributed Memory

The environment can support dynamic transfer by allowing for distributed memory. Schwartz *et al.* (2008) note that "it is hard to coordinate a jumble of concepts without distributing some of the work on the environment" (pg. 490). Schwartz provides examples of the environment allowing for distributed memory in several ways. The environment can encapsulate rules, thus relieving the need for learners to remember abstract rules. The environment can also create a visible trail of changes to support backtracking.

As students explored how inclined planes worked during the interview, they were asked to simultaneously think about several physics concepts and many experimental trials. If students did not make use of the environment for distributed memory, the opportunity to discover how the physics concepts related to inclined planes and other concepts would be diminished.

The interviews and interview transcripts were analyzed to identify episodes in which the environment appears to be supporting dynamic transfer by allowing for distributed memory. One major difference between the physical and virtual environments is that simulation performed calculations for students (for work, potential energy, mechanical advantage and efficiency) while students had to remember or look up equations and perform their own calculations when using the physical equipment. As shown in the episode below, students were reluctant to do calculations in the physical experiment.

> Patty*: Well it would… the length of your ramp, if it's longer than that's going to increase the amount of work. That will be right, right?*
>
> Interviewer*: Is there anything else you can try to explore that idea?*
>
> Patty*: Um… yes. Without doing math or just…*
>
> Interviewer*: You can do it. We have a calculator.*
>
> Patty*: Well, I'm gonna try this.* [Does experiment instead.]

In this episode, Patty could have answered her question about how length affects work in the physical experiment by calculating work. However, she chose to continue doing experimental trials rather than performing the calculation. In the simulation, calculations were performed for the students. Thus, the simulation allowed students to distribute the task of performing calculations on the environment.

Neither the physical nor virtual environment itself recorded data between trials. Thus, students had to engage the environment by making a data table to allow for distributed memory between trials. The analysis mostly uncovered instances where students had difficulty observing patterns because they failed to begin recording data. Many of these instances led students to begin keeping a data table.

In the following segment, Sam is using the inclined plane simulation:

> Sam: *Um... um... the shorter, the shorter length with more force had more efficiency? I think… I don't remember what the force was*.

Sam was trying to describe how changing the length of the inclined plane would affect the efficiency. When the surface has friction, using a longer ramp will increase the amount of energy dissipated through friction, thus reducing the efficiency. However, decreasing the length to create more efficiency also increases the force needed to move the load. Thus, Sam is trying to reason about several concepts – length, force and efficiency. Since the simulation does not store information about these physical variables between trials and Sam has not recorded his data on paper, he is unable to recall the data necessary to confidently draw this conclusion.

In the following segment, Sandra was using the inclined plane simulation:

> Sandra*: I'm noticing that the length and the height does not have an affect on the work done... if there's no friction.*
>
> Interviewer*: So when you changed the height, the work is staying the same?*
>
> Sandra*: The... yeah… the amount of... work input versus work out is the same.*
>
> Interviewer*: So you're looking at... these... uh... comparing these two?*
>
> Sandra*: Mmhmm.*
>
> Interviewer*: Okay... um... how did the work when you had a short height compare to the work when you had a tall height?*
>
> Sandra*: Short height versus long height... oh. I believe I had um... oh gosh, I didn't even look at the number, I was just looking at the fact that they were the same.*

In this episode, Sandra was exploring how changing components of an inclined plane, such as the length and the height, would affect the work needed to lift a load to the top of the inclined plane. For the case of a frictionless surface, as Sandra was investigating, the length of the plane would not affect the work needed. However, increasing the height would increase the distance the object needs to be lifted and increase the work need. In the segment, Sandra refers to “work input versus work out.” In the simulation, input work refers to the work needed to lift the load to the top of the inclined plane, while output work refers to the change in the object’s potential energy from the bottom to the top of the inclined plane. When the plane’s surface is frictionless, the input and output work are equal. When there is friction, the input work will exceed the output work as some energy is lost to friction.

In the episode above, Sandra needs to make comparisons across trials in order to compare how changing the length or height of the inclined plane changes the work (input) needed. However, she is making comparisons within the trials between the input and output work. She does not appear to realize that the comparisons she is making are not relevant, as she concludes that neither the length nor height seem to affect the work needed. It appears that since the simulation only displayed data from the current trial, Sandra is making comparisons within the trial rather than across trials. The simulation would better allow for distributed memory if it allowed students to compare data from several trials.

The following episodes demonstrate a similar trend among students in the physical and virtual environments failing to record data. In the example below, Patty has difficulty remembering data from past trials in the physical experiment.

> Interviewer: *Okay. I think that's what you just did.*
>
> Patty: *Yeah.* [Laughs.] *So I did but I forgot my numbers exactly. But I messed it up but that was the gist of what I was trying to do.* [Laughs.]

Similarly, in the episode below, Sebastian realizes he cannot see a trend in force across trials because he did not record data.

> Sebastian: *Okay, so... increasing ramp length quite a bit... so by three times... so... effort force immediately... yeah... immediately my mechanical advantage increases... and my effort force… should have written that down.* [Laughs.]

These examples indicate that both the physical and virtual environments fail to sufficiently support distributed memory. Students appear to need additional support to begin keeping a data table at the beginning of their experiments.

Although, the virtual experiment did not support distributed memory by allowing for storage of data, the virtual environment did allow for distributed memory by allowing students to quickly rerun a trial when they did not remember the previous results, as in the episode below.

Interviewer: *So when we had no friction, was the length affecting the work?*

Saul: [Runs simulation.] *Not really.*

In this example, Saul seamlessly reruns a trial in the simulation to determine the answer to a question. While he had previously observed this same trend, he did not recall the trend when asked how the length affected the work in the absence of friction. The students seem comfortable in rerunning simulations to answer the interviewer's questions. In this way, the simulation allowed for distributed memory by supporting backtracking. The physical experiment required more effort to repeat trials, which made students less likely to repeat a trial to answer a question.

As shown in the examples above, the physical and virtual environments did not offer much support for distributed memory. Students performing experiments in both environments appeared to need support to recognize the importance of recording their data for ease of comparison across trials. However, the simulation did allow students to rapidly repeat trials, which served as support for distributed memory in the form of backtracking.

## 9.3 Alternative Interpretations and Feedback

Another way the environment can support dynamic transfer is by helping students overcome pre-existing ideas. Schwartz *et al.* (2008) explain that "interactions with the environment generate feedback and variability that can help people shake free of their initial interpretations" (pg. 492). I expand this definition to include affirmative feedback as well. During the interviews, students frequently offered tentative predictions about the dynamics of the inclined plane. Students were not necessarily committed to these predictions and may not have been able to accurately support them. Thus, affirmative feedback likely plays an analogous role to alternative feedback as it informed students they were on the right track.

Students likely have prior ideas about inclined planes from their real world experiences with ramps and possibly from prior science instruction. These prior ideas may be in conflict with the science concepts they are intended to learn in the inclined plane curriculum. The interviews were analyzed to identify examples of how the environment provided alternative interpretations and feedback to overcome pre-existing ideas and affirmative feedback to support fledgling ideas.

In the following segment, Patty is using the physical equipment to explore which inclined plane would be the most useful to lift the load.

> Interviewer: *Okay. So did you want to try out some of these things? We also have…*
>
> Patty: [Uses materials to create a ramp] *That's pretty rough. That is significantly less number of Newtons. I'll try this.* [Makes ramp with short board.] *So that's more than this with the wax paper. I would probably go with the lowest angle that you can get with the wax paper.*

In the segment above, Patty tests several surfaces on the inclined plane, including sandpaper and wax paper. She correctly concludes that an inclined plane with a small angle of inclination and a smooth surface, such as wax paper, would be a good method for lifting the load. The words Patty uses to describe her experience indicate that the physical equipment provided useful feedback. She describes the surface as "pretty rough" and the difference in force as "significantly less Newtons". So it seems the physical experiment clearly conveyed information about the difference in surfaces and the difference in applied force needed for different surfaces. While it is not possible to discern whether the feedback was alternative to or affirmative of her pre-existing ideas, the feedback it provided was clear and useful.

In the following segment, Preston is using the physical equipment to explore the energy needed to lift a load using different inclined planes with friction present.

> Preston: *Well of course we already just showed that. The fact that we took this and we measured the amount of force applied over this distance.* [Moves spring scale up ramp.] *And that was the work involved...you know...2.7 joules you know as opposed to moving it just straight up and applying less energy. And so the length of the ramp made some form of difference. Of course we can use two ramps and we could...you know...make similar calculations.* [Gets a shorter board and makes a ramp.] *With a shorter ramp and friction is going to play less of a role because that force is happening over a shorter amount of time. Four Newtons of force over probably, it's probably 30 centimeters. So 4 Newtons, 4 times .3 {{uses calculator}} 1.2 joules, so you're actually, with this ramp, you're using less electrical energy because at this point friction is affecting it less than on that ramp or the longer ramp. Now of course it's still more energy than it would have been if you would have just lifted it straight up and had given it that potential energy, there's still friction adding to it but it's*

> *adding less than if you used the longer ramp. And assuming that your equipment can handle that amount of force then...you know...this ramp would have been advantageous over the longer ramp in this case.*

In the episode above, Preston uses the physical equipment to explore how ramp length affects the work needed to lift the load with friction present. He is able to measure force and distance and calculate work. The physical experiment demonstrates the correct trend that as the length increases, more work is needed to lift the load to the same height. Preston is able to correctly explain that friction adds more work on the longer board than on the shorter board. At the same time, he also discusses that the force would be higher for the shorter ramp. For this question, where the students were asked to reason about friction, it appears the physical manipulatives provided useful affirmative feedback about work.

In the segment below, Sebastian is using the simulation to explore how changing the length of the inclined plane affects its mechanical advantage.

> Sebastian: *Okay, so... increasing ramp length quite a bit... so by three times... so... [if force] immediately... yeah... immediately my mechanical advantage increases... and my effort force... should have written that down…*

In the simulation, students could choose which quantities to display. In the segment above, Sebastian has mechanical advantage displayed as a bar chart. Thus, as soon as he begins a trial for a new length he can see the results. Sebastian’s language indicates that the simulation provided instant feedback when he says, “immediately… yeah… immediately my mechanical advantage increases.”

In the segment below, Sabine is using the simulation to explore how changing the ramp length affects the work.

> Interviewer: *So what are you looking at?*
>
> Sabine: *Just the different ramp lengths because at first I just thought that the shorter ramp would work, but then it seems also the longer I guess to an extent is going to work as well. Or to a certain length I guess.*
>
> Interviewer: *And so what do you mean by it will work?*

Sabine: *Being consistent at 4.9, 4.8. But I guess that's because there is no friction, so since there is no friction, really nothing is going to affect it.*

Sabine indicates that she had initially thought that only a shorter length inclined plane would keep the work the same to lift the load to a constant height. However, the simulation provided the alternative interpretation that the work would remain the same for a longer ramp. This experience assists Sabine in realizing that the work is constant because the ramp has no friction.

The simulation also provided alternative interpretations by allowing the students to explore a frictionless environment. In the segment below, Sandra was trying to identify why the input work (work done to lift the load using the inclined plane) was greater than the output work (change in the load's potential energy).

Interviewer: *So do you have any thoughts about why shortening the length would increase your efficiency?*

Sandra: *Probably because the distance traveled would be smaller. I'm thinking if the distance is smaller the less work you have to do 'cause force times distance is work.*

Interviewer: *Did your work go down?*

Sandra: *Yeah, the amount of work I did went down but the output is still very much less. It's 43% less than the input.*

Interviewer: *Okay. And do you remember why those are different?*

Sandra: *The effect of the work I did was very much less. Like I put 1.14 Joules of energy out there and it gave me .65 Joules of product. So that was bad, I lost a lot of energy to friction probably or to some other thing.*

Interviewer: *How could we see if it was friction you were losing the work to?*

Sandra: *To see if it was friction I could put in zeroes.* [Runs simulation.] *Oh, it definitely was friction. Definitely was friction. It wasn't the load, it wasn't the ramp height. So friction is a big negative.*

The simulation allowed Sandra to run a trial with no friction, which enabled her to isolate the presence of friction as the factor that made the input work greater than the output work.

Similarly, in the segment below, Shelby made use of the frictionless environment available in the simulation to develop her ideas of force and work.

> Interviewer: *Okay, um... so in the case where there's no friction, um, which of the things are, are allowing you to predict how much work you have to do, so you said gravity... anything else?*
>
> Shelby: *The... weight of the box and…. the ramp length and steepness…*
>
> Interviewer: *Okay, so when... we have no friction, how do you think the length would affect the work?*
>
> Shelby: [does simulation] [oooohhh] *It decreased the force even if there's no friction...*
>
> Interviewer: *Okay, um and does it affect the work?*
>
> Shelby: *Nope, it's the same.*
>
> Interviewer: *Okay, do you have any thought about why that is?*
>
> Shelby: *Because it's still going to the same height…*

In this episode, Shelby appears surprised that, in the absence of friction, increasing the length of the inclined plane decreased the necessary applied force while not affecting the work needed. Initially, she predicted that the length was necessary to predict the amount of work needed to lift the load in the absence of friction. This experience helps her to realize that the height to which the load needs to be lifted determines the work needed.

The interview analysis also revealed several instances where the manipulatives did not provide clear feedback. In the episode below, Philip is exploring how changing the length of the inclined plane affects the force needed to lift the load.

> Philip: *Wait, how was that more Newtons if that was shorter? Probably just ’cause I wasn't sliding it up very straight ’cause yeah, this is only .52, this was ramp... One. That was Three, that was the third... second longest one... this should have…been a lot lower for Newtons... or this one should have been a lot lower than that…*
>
> Interviewer: *Oh, okay.*
>
> Philip: *I don't know, [haha] it's 30…*

Interviewer: *You got 5.2 Newtons on this short one?*

Philip: *Yeah... that one's fine but on this one, I should have had a lot less than 5, I think.*

Interviewer: *Okay, do you want to try that one again?*

Philip: *It just was jumping all over the place though... [Tries the board again.] It might be or just that I'm getting it started dragging it really flat, I don't know why it got started so easily on this steeper one... I feel like I'm going against physics right now.*

Interviewer: *So this one's giving you the same...*

Philip: *It's taking about... 42 to keep it steady going up it and that's higher than it was to go up the steeper one.*

Interviewer: *That is interesting... Okay.*

Philip: *I feel like our... application is not following the rules.*

In the episode above, the physical equipment that Philip is using does not appear to demonstrate the trend that the force needed to move the load should decrease when the length of the inclined plane is increased. Instead, Philip's measurements indicate that more force is needed for a less steep ramp. Philip is aware that the pattern he observes is not correct, and discusses possible causes of the inaccurate measurement, including difficulty getting and keeping the load moving. In this segment, because Philip is aware of the correct pattern, the failure of the physical equipment to provide accurate feedback does not keep him from learning. However, a student who lacked this prior knowledge could have more difficulty due to the measurement inaccuracy.

Although Philip is getting unclear feedback from the physical experiment, the environment does indeed provide an alternative interpretation. Philip initially expects that creating a less steep inclined plane by using a longer board will require less force to move the load than a steeper, shorter ramp. When Philip observes the opposite in his experiment – the shorter (steeper) ramp required *less* force than the longer (less steep) ramp – he was prompted to consider alternative explanations for this result. He discusses that the reading on the spring scale is jumping around and that the higher reading may be from having a difficult time getting the load to start sliding on the longer ramp. For Philip, this may have been a valuable learning experience, since the inconsistency in the measurements prompted him to consider alternative reasons for measurement error. However, as mentioned above, a student with less prior knowledge than Philip may not have had the same ability to learn from this experience. One such episode is demonstrated below.

The episode below provides an example of a student who has more trouble developing the idea that force needed decreases when ramp length is increased.

> Penny: [Moving board.] *And like starting from...* [Pulls block up ramp]. *Mmm. It hasn't changed significantly. I think maybe down here when it's flatter it is a little lower. Yeah. So I guess it is less steep down here. So it kind of does... it feels easier to pull it right there...but I don't know if that's like, because I'm... it's a visu... I don't know. It isn't... I'm not seeing clear results from this.*

Penny initially had the idea that the inclined plane’s steepness increased moving up the ramp. Based on this idea, she thought it would take more force to move the load at the top of the ramp than at the bottom. Penny states that she is “not seeing clear results” from the physical experiment. The force reading provided by the spring scale varies as the load is moved up the ramp, and this variation is enough to keep Penny from realizing that the force needed is constant over the whole inclined plane. Thus, in this episode, the physical equipment fails to provide a necessary alternative interpretation. Later, Penny comments on her confusion:

> Penny: *But it was only on the last trial that I could really see that, so... It might have just been my speed and stuff, too... Or that I wanted it to change so bad! There was an illusion.*

As in the previous episode with Philip, Penny is eventually able to provide physically correct reasons that the force reading changed as she moved the load up the ramp. She explains that she may have been interpreting the data from the physical experiment to support her idea. The fact that the feedback provided was open to Penny’s own interpretations and biases provides further proof that the physical experiment was not able to provide a clear alternative interpretation in this situation.

In the above episodes, the physical and virtual manipulatives provide feedback and alternative interpretations in several ways.  When using the physical equipment, the students could receive tactile feedback, by feeling the change in surface roughness between the board and sandpaper or the change in force between a long ramp and a short ramp.  This type of kinesthetic experience is not possible in the simulation.  However, the simulation can provide immediate feedback about abstract quantities, such as work and mechanical advantage.  While students who used the physical equipment needed to make calculations to determine the values of abstract quantities, the students who used the simulation were able to view those values immediately in the form of bar charts.  These two differences appear to be innate advantages of the physical and virtual manipulatives, respectively.

In addition, the simulation was able to provide alternative interpretations by allowing students to explore a frictionless environment.  As shown above in the episode with Preston, the physical experiment provided useful feedback about work in the presence of friction.  However, students could not use the physical equipment to explore work in the absence of friction, as Sandra and Shelby did in the simulation.  In the physical experiment, students were provided three surfaces: wood, sandpaper and wax paper.  Additional materials, such as wheels or an oiled, slippery surface, could be provided to allow students to explore even lower friction surfaces using physical equipment.

Two episodes were presented in which the physical equipment failed to provide useful feedback.  In both episodes, students had trouble getting accurate readings from the spring scale.  In the physical experiment, students may get inaccurate force measurements for a number of reasons, including pulling the load at an angle rather than parallel to the ramp and accelerating the load rather than pulling it at a constant velocity.  This is not a problem in the simulation since it has been designed to only move the load at the minimum applied force.  In the episode with Philip, this experience did provide alternative interpretations and prompted him to consider reasons that his observations did not match his expectations. Additional support could be provided in the physical experiment to help students identify and avoid causes of inaccurate force measurements.  Alternately, in a well-managed laboratory experience, students could be allowed to experience these alternative interpretations and helped to construct explanations for them.  However, as in the episode with Penny, students may not know a measurement is inaccurate if it supports their ideas. In this instance, it is likely that the physical equipment will fail to provide a necessary alternative interpretation.

## 9.4 Candidate Structures

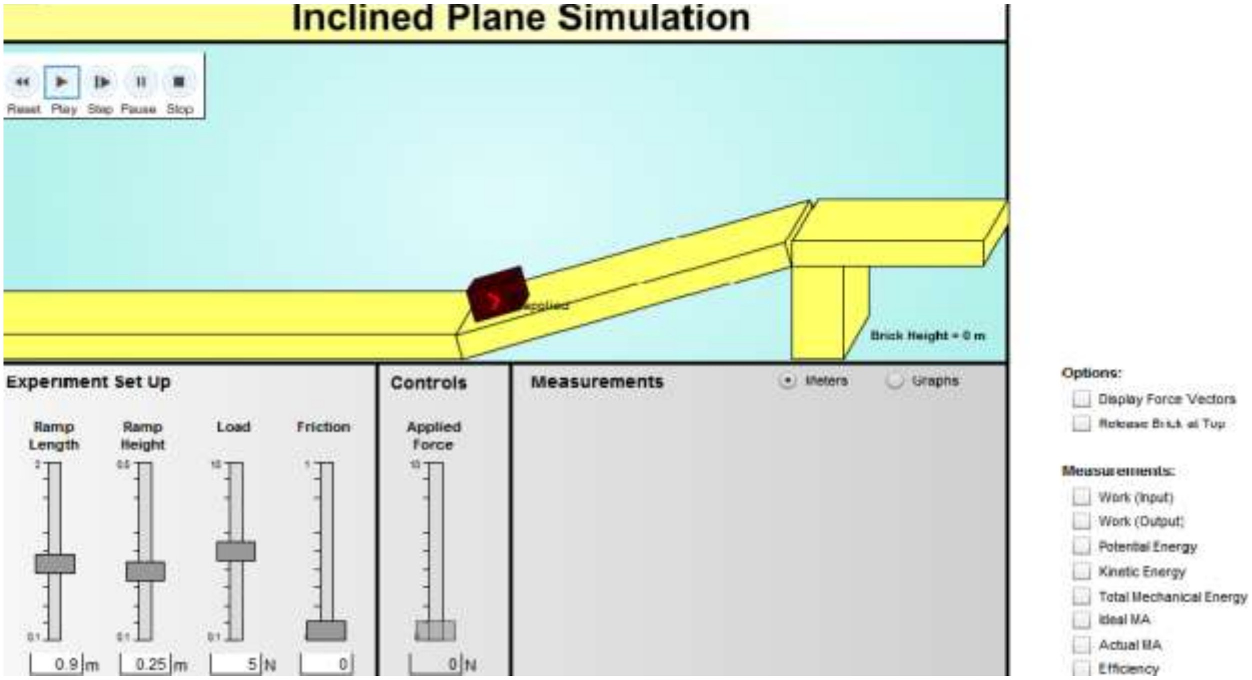
The environment can also support dynamic transfer by providing candidate structures and constraining and structuring possible actions. Schwartz points out a candidate structure is similar to a scaffold, in that both assist a novice in engaging in expert-like behavior. In both cases, the goal is that the learner will internalize the candidate structure or scaffold and be able to continue the behavior with the structure or scaffold removed.

During the inclined plane interviews, students were asked to consider many abstract variables at the same time. Students may not have much prior experience in making these types of comparisons without support from instructional materials. Since students were not provided with direct instructions, their ability to productively make these comparisons is likely tied to the candidate structures for comparison provided by the environment.

The interview analysis revealed instances where students performing the virtual experiments used the simulation as a candidate structure. In the episode below, Saul uses the simulation as a source of ideas that may be useful to consider.

> Interviewer: *So what different kinds of energy have we talked about with the ramp?*
>
> Saul: *Um...*[looks on computer] *I guess we haven't really talked about it. I think over here* [list of concepts in simulation] *has kinetic and potential energy. And I guess like, potential energy is just going to be like... like whether it's at the bottom of... like potential energy has to do with the height... like it has... I can't remember exactly but I think increased height. Like if it has to move a larger upwards distance, like it's going to have more potential energy than if it just had a shorter distance. And then with kinetic energy, that would just be like energy in motion, so like as it's moving it's going to be increasing in kinetic energy 'cause you're moving it more and decreasing in potential energy because you're decreasing the amount of like height the object has to move.*

As shown in the screenshot in Figure 9.2, the simulation includes (at bottom, right) a list of variables that the student can select to observe. The default setting is that none of the variables are selected and no measurement bars appear, as shown. The list of possible measurements includes work (input), work (output), potential energy, kinetic energy, total mechanical energy, Ideal MA (mechanical advantage), Actual MA and efficiency.  While the intended purpose of this list is to allow students to choose which variables to measure, in the episode above Saul uses the list as a collection of quantities that could be considered when talking about the inclined plane.  When the interviewer asks him what types of energy they have previously discussed, his body language (looking at the computer) and language ("over here has") indicate that he relies on the list in the simulation to come up with the ideas of potential energy and kinetic energy.  Once these ideas have been provided by the simulation, Saul begins to discuss them in terms of the inclined plane.



Ramp Length 0.9 m
Ramp Height 0.25 m
Load 5 N
Friction 0
Applied Force 0 N

Figure 9.2 Inclined plane simulation.

In a different episode, Sandra appears to get the idea of energy conservation from the bar graphs pictured in the simulation.  In the episode below, Sandra has just started using the simulation.  She has chosen to display the measurements of work (input) and work (output).  In the simulation, work (input) refers to the amount of work that would be required to lift the load using the inclined plane, while work (output) refers to the amount of work needed to lift the load straight up, or equivalently to the change in the potential energy of the load during the lift.  She has left the length, height, load and friction set to the defaults, so the friction is set to zero.

Interviewer: *So what are you seeing?*

Sandra: *What is that they say… energy… is conserved... energy input... what's the word I'm looking for? Equal and opposite, like energy can never be created or destroyed.*

Interviewer: *Yeah, you said conserved.*

Sandra: *The reason why I say that I notice here I put 1.5 and I'm getting out 1.25, 1.25 and 1.25, so is that like the energy conservation going on here.*

Because the friction is set to zero, Sandra observes that the work (input) and work (output) are the same. Since she has the measurements depicted as "meters", or bar graphs, she observes both bars rise to the same height and reads off that both rise to 1.25. The structure of this presentation provokes Sandra to think about energy conservation. She clearly states that she is thinking of energy conservation because she sees she's getting out what she puts in. It appears the simulation provides a useful candidate structure for the target concept of energy conservation.

In the episodes above, the student spontaneously used the simulation as a candidate structure. In other instances, the interviewer had to direct the student to consider the simulation as a candidate structure. For example, prior to the episode below, Sam has been asked to consider how he could predict the electric bill for a motor that is used to pull the load up an inclined plane. The interviewer asks him what science concepts are related to the electric bill, and he begins to talk about voltage.

Interviewer: *Umm.. do you know what voltage is? What kind of thing voltage is? Umm... so if you look at these different things that we have to possibly use over here, umm, which one of these would be closely related to what your electric bill would be?*

Sam: *Umm... the energy?*

Interviewer: *Okay? And which one?*

Sam: *Mechanical energy?*

In this episode, Sam did not spontaneously use the simulation as a source of science concepts from which to choose one that could be related to the electric bill. However, when he appeared to have difficulty, the interviewer directed him to use the list as a candidate structure, or source of ideas. While the concept Sam chose (mechanical energy) is not the target concept (work (input), discussing mechanical energy is useful for the question he is trying to answer. Mechanical energy follows many of the same trends as input work, but does not account for energy lost to friction. Thus, Sam could use the concept of mechanical energy to make predictions about the electric bill, and a productive discussion could occur when he observes that mechanical energy does not change when the surface of the ramp is changed.

Similarly, in the episode below, Sabine is trying to identify the factors that affect the work needed to lift the load using the inclined plane. She has been running trials with the measurements for work (input) and total mechanical energy displayed.

> Interviewer: *So up on the screen you have the work and the total energy. And that's the potential energy plus the kinetic energy. Have you noticed anything about those two bars while you've been doing the trials?*
>
> Sabine: *Most of the time they're the same.*
>
> Interviewer: *Okay. Do you have any thoughts about what might make them the same or what might make them different?*
>
> Sabine: [long pause] *No.*
>
> Interviewer: *Okay. So right now we have the friction at zero, and they're the same. So if we try a trial real quick where there is some friction.*
>
> Sabine: [runs simulation]
>
> Interviewer: *And what does that do?*
>
> Sabine: *They're different.*
>
> Interviewer: *Okay, and which one's bigger?*
>
> Sabine: *The work.*
>
> Interviewer: *Do you have any thoughts about why the work would be higher?*
>
> Sabine: *Because more work is needed to be done to get it past the friction.*

In the episode above, the interviewer introduces the candidate structure of comparing the meters (bar graphs) representing work (input) and total mechanical energy. This is similar to the candidate structure that Sandra used spontaneously. In this episode, while Sabine does not make use of the candidate structure spontaneously, she is able to use it fruitfully once it has been identified. By comparing the bar graphs, she is able to develop the idea that work (input) is greater than total mechanical energy when friction is present because more friction requires more work.

The interview analysis did not reveal any examples of the environment created by the physical equipment providing candidate structures for the students. However, the interviewer did attempt to develop candidate structures using the physical environment. In the episode below, the interviewer is trying to help Paul notice a specific trend: when a smoother surface is used, the difference in the work needed to lift the load to the same height using ramps of different lengths decreases. Recognizing this trend could potentially help Paul reason that work would not depend on length for a frictionless ramp. Earlier in the interview, the interviewer had tried to get Paul to make this comparison. Here, the interviewer is leading Paul through the comparison.

Paul: *Long wood, long wax, 3.6. ((mumbles)) So the short one had really less change, less change of, uh, work than about .6 joules, er, for then... for about .3 joules*

Interviewer: *Okay. Um, and we if we look at -- say we look at the wood surface, um, for the two different lengths. This time we have 3.6 to 1.5 which is... I should be able to subtract in my head. So here we have a difference in 2.1 joules, um, from the short ramp to the long ramp.*

Paul: *Mhm.*

Interviewer: *And here we have -- I think that's gonna be 1.8. So the difference here is 2.1. And the difference here is 1.8.*

Paul: *Yeah.*

Interviewer: *Do you have any thoughts of why that difference shrunk, or do you think it's...really changing or is it just our calculations.*

Paul: *I think it's changing because -- because it has a shorter, I mean it has a smaller kinetic energy over a longer of time.*

Paul did not spontaneously make comparisons between trials to explore how a smoother surface affected the difference in work for different lengths of ramps. While the interviewer was able to step him through this comparison, Paul was not able to extrapolate the relationship that the difference in length affects the work less for surfaces with a lower coefficient of friction. Instead, he related the difference in work to kinetic energy. This episode represents a failure of the physical environment to create a useful candidate structure for the student.

In the episode below, the interviewer again tries to use the physical environment to create a candidate structure. In this episode, the interviewer is trying to help Patty recognize the trend that the work gets closer to the change in potential energy for ramps with smoother surfaces.

Interviewer: *And how does that work compare... or how does that energy compare to the other two?*

Patty: *Um... other.* [Laughs.] *Explain it to me.* [Both laugh.]

Interviewer: *So if we look... let's real quick try to flip this guy over* [referring to sandpaper board] *and calculate the work when we're using a smoother surface.*

Patty: [Calculates work.] *2.4.*

Interviewer: *Okay. So when we changed the surface to smoother how did it...?*

Patty: *The amount of work was much less.*

Interviewer: *Yeah. And then so it got closer to our potential energy. So what do you think would happen if it kept on making it smoother and smoother and smoother?*

Patty: *Then potential energy and work would almost be equal.*

Interviewer: *Okay. So then if we got rid of friction what do you think would happen?*

Patty: *Would it be less then the potential energy?*

Interviewer: *Well it would end up being the same. Do you have any thoughts about why it's different when it becomes the same?*

Patty: *Um... just because the amount of force would be less.*

In this episode, Patty relies on the interviewer to guide her through the comparison of work and potential energy for ramps of different surfaces. The physical equipment does not create a candidate structure that helps her to spontaneously make this comparison. The interviewer explains the relationship that the work gets closer to the change in potential energy when the surface of the ramp is smoother. However, Patty is still not able to extrapolate that the work and potential energy would be the same for a ramp with no friction. Thus, she does not observe an application of energy conservation and instead relies on the less fundamental idea that a smoother surface requires less force than a rougher surface.

The environment may create candidate structures by structuring the constraining students in productive ways. However, the interview analysis uncovered several ways in which the physical and virtual environments over-constrained students. In the physical experiment, students expressed interest in experimenting with additional types of boards. Two examples are shown below.

> Patty: *Um...well if you had different lengths of this one with the sandpaper on it you could test it with the same height of the truck beds and find your force and measure the distance and then see experimentally if it worked or not. If it worked the same as the smooth boards.*
>
> Philip: *In any case you'd want the smoothest ramp possible to reduce friction, and as far as height, again you'd just have to find the one with the most efficient... like when do you pass that point where the ramp's going, like when are you going too far. So you want the one that's like the most... like you'd have to come in from both sides and figure out which one's going to be shorter. We didn't have all the lengths but... does that make sense?*

In the future, the physical equipment could be modified to include the type of equipment described by Patty. Students were only able to test one length of board with the sandpaper surface. Additional board lengths would need to be covered with sandpaper to allow students to explore more possibilities. However, it would be impractical to modify the physical equipment in the way described by Philip. In essence, he is describing the ability to continuously change the length, as can only be done in the simulation.

The analysis also revealed instances of the simulation over-constraining students. Two examples are shown below.

> Sabine: *Okay. I guess given this you would want the longest ramp that you would have which is two meters I guess.*
>
> Sandra: *So we don't have anything to change the smoothness or roughness in this simulation so I didn't even think about that.*

In the first example, Sabine expresses interest in testing the “longest ramp”. Although the simulation allows students continuously change the length of the inclined plane, the length can only be increased to two meters. It would be possible to include additional lengths to allow students to explore the advantages and disadvantages of ramps of greater length. In the second example, Sandra thinks she cannot change the surface of the ramp. The simulation does in fact allow students to alter the surface through the slider labeled “friction”. However, a constraint of the simulation is that the friction is not directly related to a physical difference in ramp surface. Additional support could be provided to the student to explain that the “friction” slider is related to the surface of the ramp.

Overall, the simulation is better able than the physical experiment to provide candidate structures for the students. It appears that the presence of list of variables from which the students can select their measurements is useful in supplying students with a reminder of science concepts that are useful to consider in the context of the inclined plane. A similar list is provided by the concept map in the CoMPASS hypertext system. However, students did not frequently return to the hypertext system, and were more likely to rely on the list in the simulation. In addition, the meter, or bar graph, depiction of the measurements in the simulation helped students to make productive comparisons between variables. In the episode with Sandra, this comparison allowed her to recognize energy conservation in the absence of friction. The interviewer attempted to guide students through similar comparisons in the physical experiment, but as shown in the examples with Paul and Patty, these experiences were not as fruitful.

The analysis also revealed instances of both environments over-constraining the students. Some of these constraints could be alleviated by providing additional equipment or information. However, some of the constraints were more essential to the nature of the environment. For example, in the physical experiment, it is impractical to have many ramps of around the same length. However, in the simulation it is easy to allow students to change the length as a continuous variable. On the other hand, some students have difficulty connecting changes in the simulation, such as adjusting the "friction" slider, to the physical changes they represent. In the physical experiment, each change is directly related to the physical system.

## 9.5 Focal Point for Coordination

Finally, the environment can support dynamic transfer by serving as a focal point for coordination by helping students to bring together different pockets of knowledge. The environment can help students to combine ideas they may have not thought to combine on their own. In the inclined plane interview, students were challenged to make complex comparisons about several concepts (force, work, potential energy, friction). Students often had difficulty reasoning about several concepts at once. The environment can assist students in bringing together several pockets, or disconnected pieces, of knowledge in a productive way.

Below, I discuss two different types of focal points for coordination. In the first type, the environment helps students to bring together useful knowledge components simultaneously. In the second type, the environment helps students bring together useful knowledge components across time, or from different experimental trials.

The interview analysis revealed several ways that the simulation served as a focal point for coordination. In the episode below, Sebastian discusses the concepts of input work, output work, mechanical advantage, force, distance and efficiency.

> Sebastian: *That will make our ... input work as close as possible to our output work so we're doing as much actual work... the mechanical advantage is determined by the effort force and the distance so you would want a higher mechanical advantage but the effort force in this case is what is most important.*
>
> Interviewer: *Okay… umm… so yeah... we were before talking about mechanical advantage and what you think effort force is.*
>
> Sebastian: *Yeah, because mechanical advantage may be... mechanical advantage is actually umm even a little misleading because it's over a larger distance so... as your mechanical advantage gets larger, your efficiency can go down so while you do want some mechanical advantage of course because that is... you know... lowering your effort.. force… well, a measure of lowering your effort force… but it also negatively affects your efficiency.*

In the episode above, Sebastian discusses that while a longer ramp will create a larger mechanical advantage, the longer ramp will also decrease the ramp's efficiency. Thus, he demonstrates a sophisticated understanding of the effects of increasing the length of an inclined plane that has friction. While it may not be clear from the transcript, Sebastian's discussion was greatly supported by the virtual environment. He was using the meter, or bar graph, view of many variables. This view created a focal point for coordination by bringing together the variables in one location and simultaneously displaying the effects of changing the length on each.

On the other hand, the analysis only revealed instances of students in the physical environment struggling to understand abstract quantities. In the two episodes below, a student using the physical equipment struggles to compare ideas that would be easy to compare within the focal point for coordination created by the simulation.

> Interviewer: *So how... do you have any ideas about how the number for the work is compared to how the number for the potential energy is at the top?*
>
> Patty: *Work... work would probably be when it reaches the top... the potential energy would be at the greatest amount. And the amount of work you put into it is determined... I don't know.* [Both laugh.] *Work, potential energy... I'm lost.* [Laughs.]
>
> Preston: *Of course this scale won't measure energy, it'll measure weight of course you can take that... and I'm trying to think how to convert an object's mass and its height to gravitational potential energy, there's an equation for that which escapes me for the moment.*

In the first example, Patty struggles to coordinate her knowledge about work with her knowledge about potential energy. In the physical experiment, nothing in the environment creates a useful representation through which students can make this comparison. With the meter view available in the simulation, Patty could have easily viewed the work and potential energy simultaneously, which would have supported the development of the idea that work is greater than or equal to the change in potential energy, depending on the presence of friction. In the second example, Preston struggles to coordinate the ideas of mass and height to calculate the load's potential energy. Again, the simulation performs this coordination for the student, by allowing the student to select the load and height and display the potential energy as a measurement meter.

One specific class of coordination provided in the simulation was the coordination of the student's understanding of specific concepts with the idea of a zero-friction environment. In the episode below, Sam realizes that the ramp he created has one hundred percent efficiency because he has set the friction to zero.

> Sam: *So it says it's a hundred percent efficiency?*
>
> Interviewer: *Do you have any thoughts about why you have a hundred percent efficiency?*
>
> Sam: *Huh?*
>
> Interviewer: *Do you have any thoughts about why it's a hundred?*
>
> Sam: *'Cause there's no friction…*

In this example, Sam has already made use of the meter view to present a measurement of efficiency. The simulation allowed him to explore a frictionless ramp, which could not be created in the real world, and assisted him in connecting a perfectly efficient ramp to the ramp's frictionless surface. In the episode below, Saul uses his observations from the frictionless ramp to explain why a longer ramp requires more work than a shorter ramp when friction is present.

> Interviewer: *Okay. So when we had no friction, was the length affecting the work?*
>
> Saul: [Runs simulation.] *Not really.*
>
> Interviewer: *Does that help you think about what might be going on?*
>
> Saul: *So I guess with... so I guess in the case with friction, if you used the shorter ramp, you'd probably be working less against friction at that point and more against gravity. So I guess the friction wouldn't be as big of a factor with a shorter ramp, which can cause your motor to use less energy at that point.*

In this example, Saul coordinates his observation that changing the length of a frictionless inclined plane did affect work with his observation that length does affect work in the presence of friction. Students using the physical equipment cannot make this first observation. While all students had the opportunity to read about work and distance (length) in the CoMPASS hypertext system, students did not spontaneously coordinate the information from the reading with their observations from the experiments. However, students using the simulation productively used their understanding of the zero-friction ramp to productively explain observations about ramps with friction.

Students who used the physical equipment were not able to observe a frictionless ramp. Thus, they had to try to extrapolate to the frictionless case from their trials with inclined planes with different surfaces (sandpaper, wood and wax paper). Students frequently had difficulty with this process. In the example below, Philip is asked to consider if there is a ever a case where the work required to lift a load and the load's change in potential energy would be the same.

> Interviewer: *Do you think that there's ever a case where the work and the potential energy that you get once you get there would be the same? If they could ever be the same or why they're not the same here?*
>
> Philip: *I think it would always be more to get it up. The work would always be higher than the actual energy 'cause if you're up there than it's counting as going like down, it's counting your height but it's not really taking into account like the energy you used to get it up...like the distance and how far you went. And so I guess that the work would always outweigh the potential energy.*

Philip replies that the work will always be greater than the potential energy. In most real world situations, this is in fact the correct answer. However, students are often expected to understand and use the fact that conservation of energy implies that work is equal to the change in potential energy in a frictionless environment. In addition, Philip's reasoning about why the work exceeds the change in potential energy is not sufficient since he does not attribute the difference to the presence of friction. As shown in the previous examples of students using the virtual environment, the frictionless trial available in the simulation frequently assisted students in reasoning about trials with friction.

The episode with Paul below demonstrates the same trend. Paul is asked to consider whether two different boards could ever require the same work to lift a load.

> Interviewer: *So if we think of keeping the, the height the same, do you think that there's any case that we could get two different boards that would require the same work to get to the top of the ramp?*
>
> Paul: *So if we kept the same heights…*
>
> Interviewer: *Yeah…*
>
> Paul: *We would want the same board… [that got the]*
>
> Interviewer: *or two different boards that got the same, have the same work.*
>
> Paul: *I guess, two boards, one maybe shorter and has a different friction on it... or something on it that would cause it to have higher work than something else that has a shorter distance.*

Paul responds that two ramps of different lengths could require the same work to lift a load if the boards had different surfaces. He explains that "friction" or "something on" the shorter ramp would have to cause the shorter ramp to require more work. As in the episode with Philip above, Paul's response is correct for most real world situations. However, he is similarly not able to predict that any two frictionless ramps would require the same work to lift the same load to the same height. As previously shown in the example with Saul above, the simulation created a focal point for coordination of students' ideas about work and energy in cases with and without friction.

The episode with Patty below demonstrates the danger of not helping students coordinate the ideal (zero-friction) with their observations in the physical experiment. Patty is discussing the trend she observed that a longer board required more work to lift the load to the same height as a shorter board. The interviewer then asks her to explain why that happened.

> Patty: *Well...it didn't really matter that the incline was less on this necessarily because work was still... um... a larger value than it was so... it's contradictory.* [Laughs.]
>
> Interviewer: *So do you have any thoughts about maybe why it was more in that case? Why the work for the longer ramp was more?*
>
> Patty: *Um... probably just because the length was substantially longer than the really short one. So maybe if it were a little bit shorter then um... it might be less than the really super big one.*

> Interviewer: *So you said something was contradictory?*
>
> Patty: [Laughs.] *Like... I guess it's not really contradictory but I kind of contradicted myself when I said that the lower the incline the less amount of work you put into which isn't necessarily true because... according to this...* [Laughs.] *Just because you're having to push or pull that object a further distance on maybe not such a smooth surface. So the further you push it the more work you might be putting into actually getting it into the truck.*
>
> Interviewer: *Okay. Do you have any thoughts about if the distance would ever not be having this effect?*
>
> Patty: *If we didn't have gravity.* [Laughs.] *Um...what distance would it have? Maybe if the like amount of friction were not as great. So probably on a really smooth, smooth waxed surface.* [Laughs.]
>
> Interviewer: *Okay. And what would happen in that case do you think?*
>
> Patty: *Um, there might not be any work involved at all.* [Laughs.] *The amount of force used wouldn't be as great so if they were both like nearly the same... oh that still wouldn't work.* [Laughs.]
>
> Interviewer: *So what were you thinking?*
>
> Patty: *If both of the forces were about the same then it wouldn't matter because you would still be putting more... like the same amount of work into it even if the distance were longer. So it would still kind of show the same relationship.*

Patty first supposes that the longer board required more work than the shorter board because there is a drastic difference in length. She does possibly attribute the difference in work to the surface when she says "you're have to push or pull that object a further distance *on not such a smooth surface*." However, she does not continue to develop the idea that the presence of friction explains why the longer board requires more work than the shorter board. The interviewer then asks her the same question as Paul was asked above: is there a case where the length of the board does not affect the work? Patty first guesses in the absence of gravity the work might be the same, and then suggests the work might be the same for two lengths of ramps if the ramps were very smooth. She then suggests that these ramps may not require any work at all to lift the load, before deciding that she would see the same trend as in her physical experiment because the distance would still be longer for the longer ramp. In this episode, Patty twice begins to discuss that the presence of friction explains why a longer board requires more work to lift a load than a shorter board.  However, she appears to lack confidence in and is not able to fully develop these ideas.  It seems Patty would have benefited from observing the frictionless trial in the simulation since although she has activated the idea of friction as useful explain the discrepancy in work values, she is not able make full use of that idea.  This episode demonstrates the valuable role played by the virtual environment in helping students coordinate their ideas of the ideal and physical worlds.

While in many cases the virtual environment created a valuable focal point for coordination, the interview analysis revealed several cases where students had difficulty connecting aspects of the simulation to the physical world.  Two episodes for the interview with Sandra highlight potential difficulties.  Please note that throughout the interview Sandra has used the word "acceleration" to refer to the inclination of the ramp.

> Interviewer: *Do you have any ideas about what aspect of the ramp is related to friction?*
>
> Sandra: *What aspect of the ramp is related to friction? I'm thinking the acceleration part of it. So it's like you're going against gravity in some kind of way. If this was flat, you would just push straight through and push straight over. Of course you wouldn't get it up there if you were to go over, but because it's up high there you have to kind of...it's like climbing a hill.*
>
> (Later in the interview)
>
> Sandra: *Um... when the height was… lower… I lowered the height and increased the length of the ramp...umm, I noticed, that it had the same amount work input and output... same numbers actually, versus when I increased the length and reduced the height, it give me the same exact numbers.* [Student does not actually change height of inclined plane.]

In both examples above, Sandra makes mistakes that seem unlikely for a student to make in the physical environment.  In the first episode, Sandra fails to recognize that friction is related to the smoothness or roughness of the surface of the inclined plane.  She instead describes friction as related to the steepness and moving the load against gravity.  In the second episode, Sandra observes an inaccurate trend that the work input and output are the same for ramps of different heights because she does not actually change the height of the inclined plane.

Shelby described a similar difficulty coordinating the abstract representation used in the simulation with her sense of the physical world in the episode below.

> Shelby: *Physics.* [Both laugh.] *Um... it's just the way life is... um... it's really difficult 'cause I don't really know what it feels like to pull like .7 Newtons… so it's kind of hard to like... do it…*
>
> Interviewer: *Okay, um and you mean because…*
>
> Shelby: *That's just not a unit that I'm familiar... that I go to gym and I... lift in pounds that are, you know… that's something, I know what ten pounds feels like but I don't know what pulling .7 Newtons feels like.*

Shelby very articulately describes a difficulty it is likely many students face in the simulation. In the simulation, force is measured in the SI unit of Newtons. However, students do not usually have a real world sense of what a Newton feels like. As Shelby points out, it is more likely that students have a physical sense of how much effort they exert to lift a certain number of pounds, or in physics terms that they have a better physical sense of weight (in pounds) than force (in Newtons). Support could be provided in the simulation to help students get a better sense of force by explaining the amount of force (in Newtons) required to lift a certain weight (in pounds).

The simulation requires an additional type of coordination over the physical experiment because students must coordinate the variables and measurements in the simulation with their analogs in the physical world. The physical environment naturally creates a focal point for coordination because students can use their sensory perception to connect these ideas. In the physical environment, students are supported to connect their physics knowledge, like the concept of friction, with their knowledge of the real world, like how surfaces feel. However, the simulation requires more sophisticated coordination since students cannot physically touch the surface of the inclined plane or feel the force required to move the load. While the majority of students seamlessly performed this coordination, several students had difficulties as shown in the examples above.

Overall, the virtual environment more frequently served as a focal point for coordination than did the physical environment. The presence of the meter view, or bar graph, helped students using the simulation to reason about several abstract variables at once. Students using the physical equipment often had difficultly with both reasoning simultaneously about several variables and reasoning about abstract variables. In addition, the ability to run a frictionless trial helped students using the simulation to reason about friction in their other trials. In this way, the simulation appears to help students coordinate their ideas about the ideal world with the realities of the physical world.  Students using the physical experiment did not have the opportunity to observe a frictionless trial and often had difficultly reasoning about the effects of friction and predicting what would happen in the ideal, frictionless case.  Although it is important for students to learn about friction since friction is present in most physical situations, students are also expected to understand the ideal, frictionless case.

The simulation appears to help students coordinate knowledge both simultaneously and across trials.  The meter view, or bar graphs, helped students coordinate ideas presented simultaneously on the screen.  The frictionless trials helped students to see how the concepts like work behaved in both ideal and "real world" cases.  If the simulation allowed for distributed memory by storing past trials, it seems this "across-trial" focal point for coordination would be even stronger.

On the other hand, the simulation did require an additional type of coordination between the representations of variables in the simulation and what they represented in the physical world.  Students using the simulation sometimes struggled to make this connection.  For example, one student did not connect changing friction to changing the surface of the ramp, and another student discussed her confusion connecting a force measurement to a physical feeling. Additional support could be provided in the simulation to assist students with these connections.

## 9.6 Summary

Overall, the virtual environment appears to offer more support for dynamic transfer than does the physical environment.  The ways in which the physical and virtual environments were found to support dynamic transfer are summarized in Table 9.1 below.  The second table, Table 9.2, summarizes my recommendations for improving the physical and virtual environments to better support dynamic transfer.  These results are summarized in more detail below.

### Table 9.1 Summary of the Ways the Physical and Virtual Manipulatives Supported Dynamic Transfer

| | **Physical Environment** | **Virtual Environment** |
|---|---|---|
| **Distributed Memory** | | • Performs calculations<br>• Allows students to quickly rerun trials (backtracking) |
| **Alternative Interpretations/ Affirmative Feedback** | • Tactile feedback | • Immediate feedback about abstract quantities<br>• Frictionless environment |
| **Candidate Structures** | | • List of possible concepts to consider<br>• Bar graphs provide structure for comparison |
| **Focal Point for Coordination** | | • Bar graphs helped students consider several variables at once<br>• Frictionless trial helped students coordinate ideas of ideal and physical |

### Table 9.2 Suggested Modifications to Physical and Virtual Manipulatives

| | **Physical Environment** | **Virtual Environment** |
|---|---|---|
| **Distributed Memory** | • Support students to record data | • Support students to record data<br>• Store previous trials |
| **Alternative Interpretations/ Affirmative Feedback** | • Provide surfaces with less friction than wax paper<br>• Support students to identify causes of and avoid inaccurate measurements | |
| **Candidate Structures** | • Provide list of useful science concepts<br>• Provide more lengths of ramps and surfaces | • Support students to understand physical meaning of variables in simulation |
| **Focal Point for Coordination** | | • Support students to understand physical meaning of variables in simulation |

While both environments failed to offer support for distributed memory by storing data between trials, the ease of repeating trials in the simulation allowed students to backtrack when necessary. For both types of experimentation, it appears that students would benefit from support about how to record data.

Both environments were able to provide alternative interpretations and feedback. One advantage of the physical experiment is that it is able to provide tactile feedback, while an advantage of the simulation is that it can provide immediate feedback about abstract quantities. Students sometimes had difficulty interpreting the feedback from the physical experiment; while this experience can be a positive one for a well-prepared student who is able to reason about the unclear feedback, it may be detrimental to a student who does not recognize that feedback as unclear. The ability to run frictionless trials in the simulation provided a useful type of alternative interpretation that cannot be recreated with the physical equipment.

The simulation provided candidate structures for the students by presenting a list of possible variables of interest and by displaying the variables chosen for measurement as meters, or bar graphs. Students made use of the list as a reminder of science concepts it would be useful to consider. The meter presentation appeared to support productive comparisons between variables. When the interviewer tried to guide students in the physical environment through similar comparisons, the experiences were not as fruitful.

The simulation provided a valuable focal point for coordination in several ways. The meter view of the measurements helped students to consider several variables at once, or to coordinate their understanding of multiple science concepts. Students in the physical environment often had difficulty with this task. In addition, the frictionless trial provided by the simulation helped students coordinate their ideas of the ideal and physical worlds. This experience cannot be recreated with the physical equipment. However, students using the simulation appear to need support in coordinating the representations of variables in the simulation with their physical meaning.

# CHAPTER 10 - Survey Results

In this chapter, I present my findings about students' views of the physical and virtual experiments and the data collected from physical and virtual manipulatives. Students' views were elicited with forced-choice and open-ended survey questions in the CoPF09 and PWS10 studies. The studies and surveys are described in more detail in Section 4.2.3.1 and 4.2.4.1, and the surveys are included in Appendices H, I and L. These results help address Research Question 3, which asks, "Do students view the information from physical and virtual manipulatives differently?"

## 10.1 CoPF09 Study

After completing both the physical and virtual pulley activities, students (N=99) in the CoPF09 study were asked to respond to two sets of questions designed to elicit their views of the physical and virtual experiments. The questions and the results of the analysis of students' responses are presented below.

### *10.1.1 Comparison of Physical and Virtual Experiments*

The students were asked to respond to several wrap-up questions in the Activity Center after they had completed both sets (physical and virtual) of experiments. The questions, reproduced in Table 10.1 below, asked students to make comparisons between the two experiments. The worksheet is included in Appendix H. A phenomenographic approach (Marton, 1986) was used to analyze students' responses. A single student's response could fall into more than one category.

**Table 10.1 Wrap Up Questions**

| **Q #** | **Question** |
|---|---|
| 1 | In what ways was the computer simulation pulley experiment *similar* to the physical pulley experiment? |
| 2 | In what ways was the computer simulation pulley experiment *different* from the physical pulley experiment? |
| 3 | What may have caused differences between the data you got from the physical pulley experiment and the data you got from the computer simulation experiment? |
| 4 | If there were differences between the data from your physical pulley experiment and your computer simulation experiment, which would you trust more? |

Question #1 ("In what ways was the computer simulation pulley experiment *similar* to the physical pulley experiment?") asked students to describe how the computer simulation pulley experiment they had performed was similar to the physical pulley experiment. The most common categories of responses and their frequencies are shown in Figure 10.1 below. Examples of quotes categorized in each response type are displayed in Table 10.2 below.

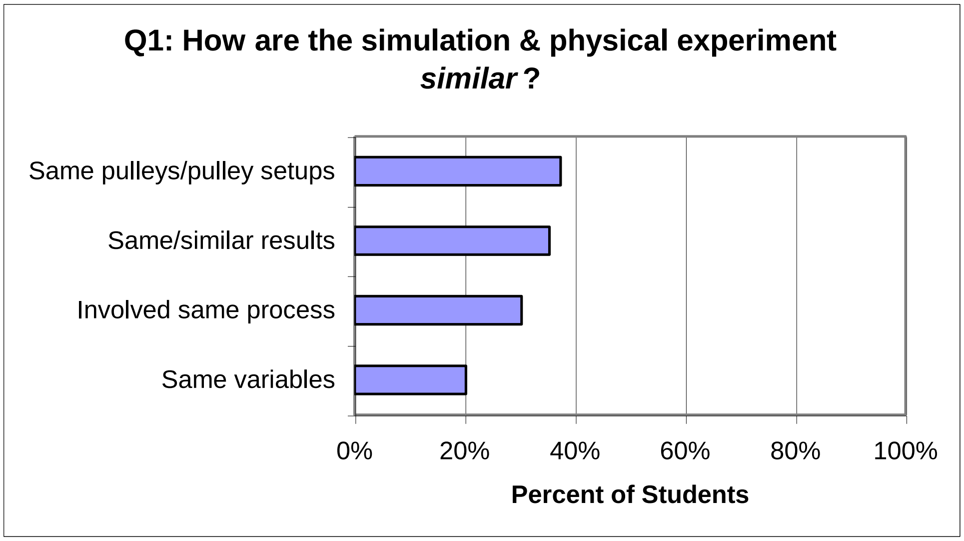


**Figure 10.1 Concepts of Physics Fall 2009: Wrap Up Question 1 Responses.**

**Table 10.2 Wrap Up Question 1: Example Student Responses**

| **Category** | **Description** | **Examples of Students' Responses** |
|---|---|---|
| Same pulleys | Discussed experimenting with the same pulley systems (i.e. single fixed, single movable, single compound and double compound) | *"The type of pulleys were the same and the distance pulled was the same as well."* |
| | | *"The simulations showed the same pulley setups and kind of tests that we did physically."* |
| | | *"It was the same concept with the pulleys and the design of the pulleys, just one was tangible and one wasn't."* |
| Same results | Discussed seeing same results in physical and virtual experiments | *"We had the same results both times."* |
| | | *"Everything was the same with the outcomes with the effort and things like that."* |
| | | *"The double compound pulley in both experiments had the greatest mechanical advantage and least effort necessary."* |
| Same process | Described the experimentation | *"It was doing the same thing that I was doing – and it was measuring the same things."* |

| Category | Description | Examples of Students' Responses |
|---|---|---|
|  | process in both physical and virtual activities as similar | *"I think they were exactly the same, only difference was that we did one ourselves and the other was already set up by the computer."* |
|  |  | *"They were very similar because we changed the pulley systems, which changed all the other factors. We recorded those changes."* |
| Same variables | Discussed changing the same variables (i.e. pulley system, height lifted) | *"We used the same pulley set ups and the distance pulled was also the same along with load."* |
|  |  | *"We set both the computer and physical pulley experiment up using same variables and conditions. The results slightly differed but not a whole lot. We also used the same type of system for each pulley in both computer and physical."* |
|  |  | *"It was the exact same thing. 1. Type of pulleys. 2. Height lifted. 3. Weight of load."* |

The most commonly mentioned similarity between the two experiments was that the same pulleys or pulley setups were used in each. The second most common type of response expressed that the two experiments had the same results. Students expressed this idea in a variety of ways, sometimes noting that the data, number or results were the same or similar and sometimes explaining that the same pulley emerged as the best, having either the most mechanical advantage or the least effort force. Another common type of response expressed an understanding that the two experiments involved the same process. Students referred to doing the same experiment, trials or "thing" with the two types of manipulatives. Some students explicitly stated that the experiments were the same except for the mode (physical or virtual). The final common type of response described the experimental parameters to be the same between the two experiments. Students referred to using the same weight as the load, lifting the load to the same height, pulling the same distance of the rope, and in general looking at the same variables. Together, these conceptions suggest that many students had a good understanding that they were investigating the same ideas in the same way in the two experiments and that those investigations had similar results.

Question #2 ("In what ways was the computer simulation pulley experiment *different* from the physical pulley experiment?") asked students to describe the differences between the physical and virtual pulley experiments. The most common categories of responses and their frequencies are shown in Figure 10.2 below. Examples of quotes from each category are displayed in Table 10.3 below.

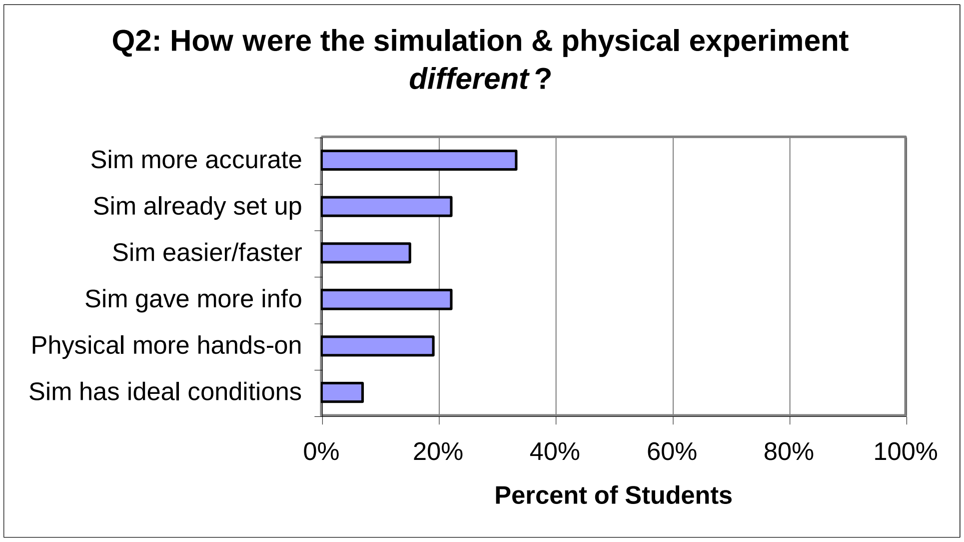


**Figure 10.2 Concepts of Physics Fall 2009: Wrap Up Question 2 Responses.**

**Table 10.3 Wrap Up Question 2: Example Student Responses**

| **Category** | **Description** | **Examples of Students' Responses** |
|---|---|---|
| Simulation is more accurate | Described the simulation to be more accurate than the physical experiment | *"Physical experiment wasn't able to get as exact numbers as the online."* |
| | | *"We came up with different results because it was harder to be exact with the physical pulley experiment."* |
| Simulation is already set up | Discussed that they had to set up physical equipment but did not have to set up simulation | *"Doing it physically made us actually have to setup the different systems."* |
| | | *"They were different because the computer had it all set up for us to just start 'experimenting.'"* |
| Simulation is easier or faster | Described the simulation to be easier or faster to use than the physical equipment | *"It went faster and wasn't as complicated."* |
| | | *"It was way easier! With just the click of a mouse the simulations were over with. The real trials were harder to do but it was good to see a real example of what we were talking about."* |
| Simulation gave more information | Discussed that the simulation provided the user with more information or | *"It wasn't hands on. It calculated the pulled distance for you; we didn't have to measure anything."* |

| Category | Description | Examples of Students' Responses |
|---|---|---|
| | calculations than the physical equipment | *"The computer did everything for us, we just 'pulled' the rope and the newtons and all that were given. In the actual experiment, we had to figure that on our own."* |
| Physical more hands-on | Described the physical experiment as "hands-on" or discussed being able to feel (i.e. feel force) in physical experiment | *"In the physical pulley experiment we got to actually pull the load; hands-on."*<br>*"We were not able to feel the work as we were in the physical experiment."* |
| Simulation has ideal conditions | Discussed that the simulation had ideal conditions (i.e. frictionless) | *"The computer simulation had no friction affecting the pulley and the physical one did."*<br>*"It was done electronically and factors like friction were not in play."* |

Students most commonly explained that the computer experiment was more exact or more accurate than the physical experiment, which had allowed for more errors. Another common response focused on the somewhat superficial difference that while students had to build the pulley systems in the physical experiment, the computer pulley systems were already set up. This may be an advantage in favor of the computer simulation because it makes the experiment quicker, but could be a disadvantage since students do not get to see how the pulley system is constructed. Students discussed many benefits of each type of experiment. They noted that the simulation was easier and faster and provided them with more information by giving measurements and performing calculations. Students also noted that the physical experiment was more "hands-on", which let them feel changes and experience the experiment for themselves. A very small number of students commented on what might be considered the "important" differences between the two experiments, such as that the simulation represented the ideal situation and was not affected by friction. Due to this, the physical quantity work was always the same in the simulation, while it varied in the physical experiment.

It is interesting that students focused on the accuracy of the computer simulation. While the computer does generate more "textbook" results, the students were given a real-world challenge as the motivation for these experiments. Thus, neither experiment yielded data that was clearly "more accurate" than the data from the other. Students also noted many of the advantages of each type of manipulative that have been discussed by researchers, such as the time and physical effort required, the match between the experimental data and the expected data, and the difference in kinesthetic experiences. Few students explicitly mentioned the important difference that the computer simulation was idealized, thus removing unwanted friction effects and leading to more "textbook" results.

Question #3 ("What may have caused differences between the data you got from the physical pulley experiment and the data you got from the computer simulation experiment?") asked students to identify the possible causes of differences between the data from the physical and virtual experiments. The most common categories of responses are shown in Figure 10.3 below, and examples of students' quotes from each category are shown in Table 10.4.

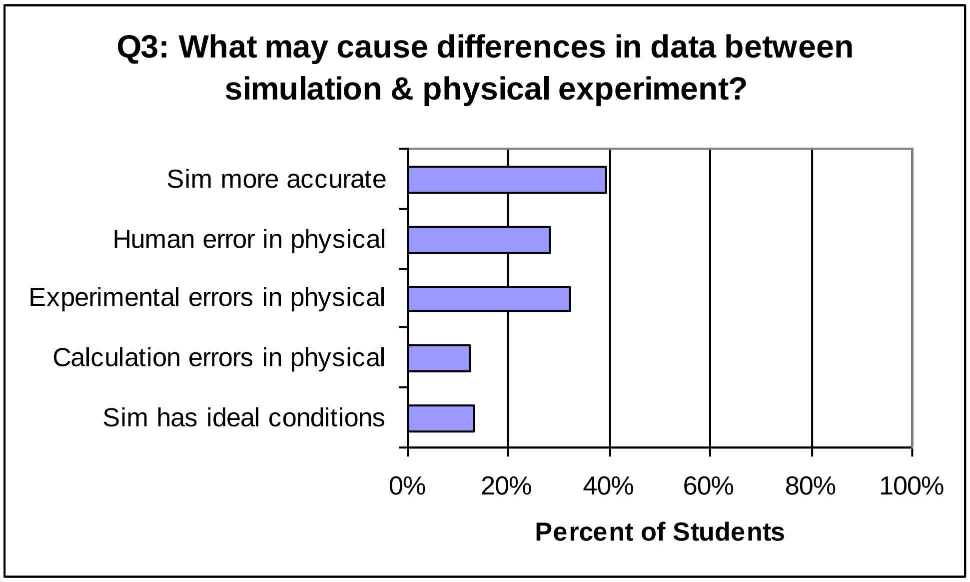


**Figure 10.3 Concepts of Physics Fall 2009: Wrap Up Question 3 Responses.**

**Table 10.4 Wrap Up Question 3: Example Student Quotes**

| **Category** | **Description** | **Examples of Students' Responses** |
|---|---|---|
| Simulation is more accurate | Described the simulation as more accurate than the physical experiment | *"Our physical pulley experiment probably wasn't as accurate. We only measured once. We didn't really know what we were doing."* |
| | | *"The physical data was an estimate or a guess where as the computer was exact and had no flaws."* |
| Human error in physical | Discussed the possibility for human error in the physical experiment | *"The physical pulley is based on human error. It's hard to get an exact number off a ruler."* |
| | | *"Errors on my half could've caused data errors/differences. The computer trials went much smoother."* |

| **Category** | **Description** | **Examples of Students' Responses** |
|---|---|---|
| Experimental errors in physical | Described particular types of experimental error in the physical experiment | *"What might cause this was how we read things when we were doing it."* |
| | | *"If we set up the pulley system wrong, or measured, or read measurements inaccurately. Also, we could have applied more force than was needed."* |
| Calculation errors in physical | Discussed the possibility of calculation errors in the physical experiment | *"If we didn't do the math right then the experiments would differ."* |
| | | *"In the physical pulley system, our calculations and data may not have been as accurate as the computer simulation experiment. This was evident because our calculations and the computer calculations did vary a little bit."* |
| Simulation has ideal conditions | Discussed that the simulation had ideal conditions (i.e. frictionless) | *"The computer simulation is ideal and without minor computing errors that we may have made in the physical activity."* |
| | | *"More correct readings of the ruler. Pulley well-oiled on computer and squeaky in physical experiment."* |

Students focused nearly exclusively on the accuracy, precision and exactness of the simulation and many types of errors in the physical experiment. While many students broadly referred to "human error" in the physical experiment, they also mentioned many possible sources of error, such as errors in their measurements and calculations, mistakes setting up the physical equipment, difficulty with the measuring tools, and the need to make estimations. Again, only a few students explicitly stated that the computer had idealized data and friction affected the results of the physical experiment. It is possible that students felt the idealized nature of the simulation and presence of friction in the physical experiment were obvious, but it is also possible that they did not know how the simulation data was produced.

Question #4 ("If there were differences between the data from your physical pulley experiment and your computer simulation experiment, which would you trust more?") asked students to identify whether they would be more likely to trust the data from their physical experiment or the simulation if the two did not agree. Students' choices are displayed in Figure 10.4. An overwhelming majority of students chose the simulation as more trustworthy than the physical experiment. The most common reasons given by these students are shown in Figure

10.5 with example student quotes in Table 10.5. Table 10.6 shows the statements made by the six students who chose the physical experiment as more trustworthy than the simulation.

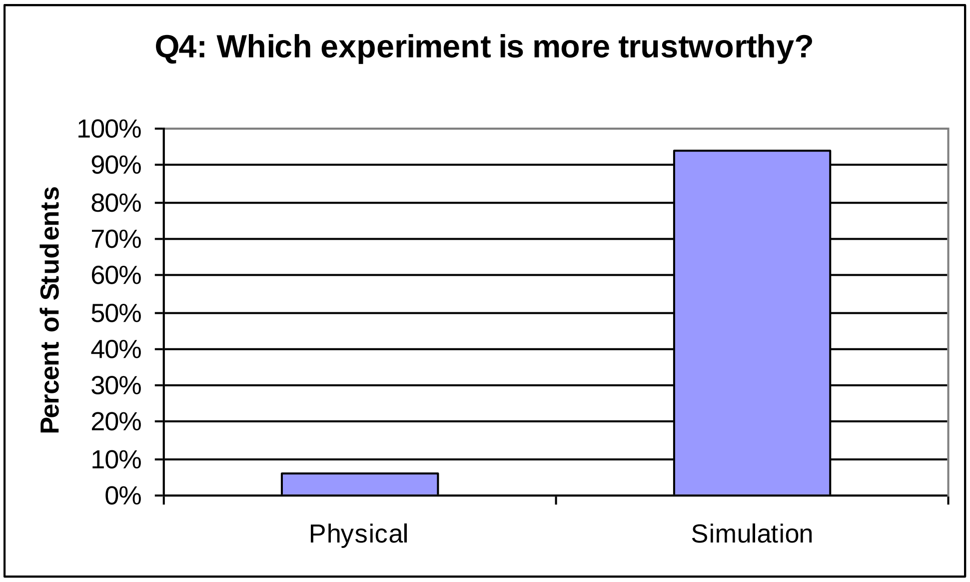


**Figure 10.4 Wrap Up Question 4 Responses.**

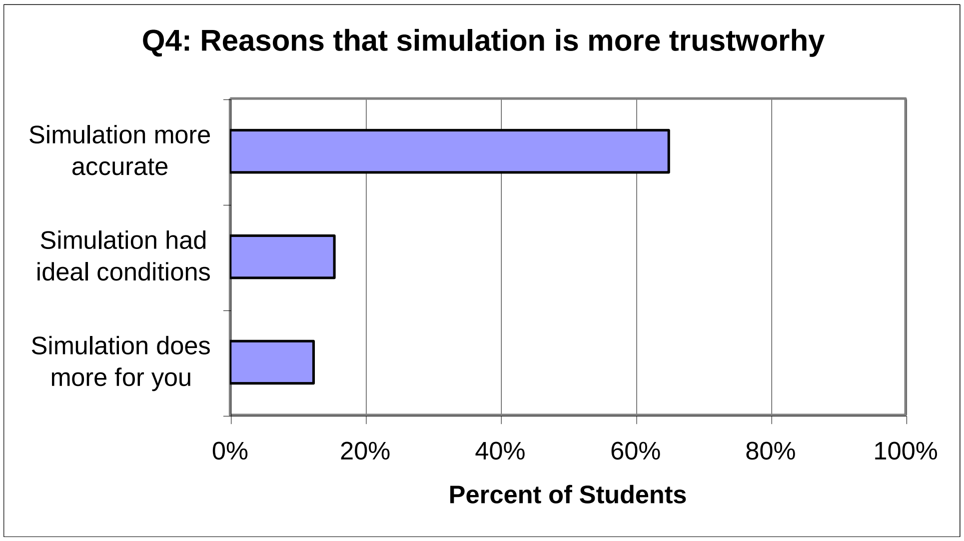


**Figure 10.5 Wrap Up Question 4: Reasoning for choosing simulation.**

### Table 10.5 Wrap Up Question 4: Example Student Responses (Chose Virtual)

| Category | Description | Examples of Students' Responses |
|---|---|---|
| Simulation more accurate | Described the simulation to be more accurate than the physical equipment | *"I would trust the computer, as humans we can make mistakes. Unless something was wrong with the computer, it would not make an error."* |
| | | *"It eliminated (mostly) the opportunity for human error, and showed more accurately the desired values."* |
| | | *"Because the measurements would be much more precise and they make more sense."* |
| Simulation had ideal conditions | Discussed that the simulation has ideal conditions (i.e. frictionless) | *"It doesn't have friction acting upon it so it makes it more reliable than the physical one with outside interferences."* |
| | | *"The computer because the simulations are made to work and I stink at physics and doing live trials so personally I would trust the computer more."* |
| | | *"Friction is not acting upon it. The data is more "real" and raw."* |
| Simulation does more for you | Discussed that simulation performed more tasks for the student (i.e. calculations, pulley system set up) than the physical equipment | *"The computer simulation because it calculated most of the information for me."* |
| | | *"Because we typed in the numbers and it did the work for us. With the physical experiment we could've strung the thread wrong or something simple like that."* |
| | | *"Probably the computer experiment because it does the measurements and calculations for you and leaves out human error."* |

### Table 10.6 Wrap Up Question 4: Students' Responses (Chose Physical)

| Student | Explanation |
|---|---|
| S1 | *"The physical experiment because it is "real life" and the computer is the perfect simulation."* |
| S2 | *"Physical one because you're able to put things and do things exactly how you want."* |
| S3 | *"Because it is more true to what would happen in real life."* |
| S4 | *"I think although the data from the computer would be more accurate I would trust ours more because we did it and saw the results for ourselves."* |
| S5 | *"Just because I can go back and recalculate it myself. Plus, the hands-on one is most likely more reliable. After all, you are doing it yourself, instead of trusting a computer."* |
| S6 | *"It is not computer generated and I did it all myself. No computer error."* |

As discussed above, an overwhelming majority of students stated that they would trust the computer simulation more than the physical experiment. Students who chose the simulation as more trustworthy than the physical experiment tended to justify their choice with the accuracy and precision of the simulation and the errors in the physical experiment. A small number of students described how the simulation data was produced, stating that it was based on the ideal, generated from a model, based on several trials, or designed correctly by someone else. A small number of students also expressed the idea that the computer "knew what it was doing", while people performing the physical experiment were not sure and had to rely on their personal abilities. Again, only a few students commented on the different effects of friction in the simulation and physical experiments. The few students who stated that they would trust the data from the physical experiment over the simulation most commonly expressed the idea that the physical data better showed what one would find in the real world, while the computer data may be too ideal or accurate.

### *10.1.2 Usefulness of Data from Physical and Virtual Experiments*

In a second survey, students were asked to choose which type of manipulative would be more useful in various situations. Each situation was made up of two or three parts: a context, a concept and a pulley setup. Students were asked about three different contexts. The test context asked students to consider whether the physical or virtual manipulatives would be more useful to check their answers on a class test. The test context questions specified different concepts (force and work) and different pulley setups (fixed, movable and double compound). The rental store context asked students to consider whether they would rather use physical or virtual manipulatives to select which pulley system to rent to lift an object. The rental store context questions specified pulley setups but not the relevant concepts since a person in this situation would likely not be thinking in scientific terms of force and work. The final context was a makeup lab; students were asked to consider whether they would rather see the data from the physical or virtual experiments if they had not been able to perform the experiments themselves in the Activity Center. The makeup lab context specified concepts but not pulley setups. There were a total of eight questions, as outlined in the Table 10.7 below. The worksheet version given to students is included in Appendix I.

**Table 10.7 Concepts of Physics Fall 2009 Survey Questions**

| **Question Code** | **Context** | **Pulley Systems** | **Concept** |
|---|---|---|---|
| Test A | Test | Fixed & Movable | Force |
| Test B | Test | Fixed & Movable | Work |
| Test C | Test | Movable & Double Compound | Force |
| Test D | Test | Movable & Double Compound | Work |
| Rental A | Rental store | Fixed & Movable | Not specified |
| Rental B | Rental store | Movable & Double Compound | Not specified |
| Makeup A | Missed lab, homework | Not specified | Force |
| Makeup B | Missed lab, homework | Not specified | Work |

This survey was given in two forms. In one version, the questions appeared in the same order as Table 10.7 above, while in the second version the rental store context questions were asked before the test context questions. The order was varied in case the first question context cued a specific response and students were resistant to changing their response in subsequent questions. For example, it seemed likely that respondents would prefer the virtual manipulative in the test context. Once selecting the virtual manipulative for several questions, students may have been resistant to change their answer in the following questions. Students' responses from the two versions were combined to reduce the effect of this possible behavior.

For each question, students were asked to choose whether the physical manipulatives or virtual manipulatives would be more useful or whether both would be equally helpful. Students' responses are displayed in Figure 10.6 below. A chi-square goodness-of-fit test was used to analyze whether students were equally likely to choose each manipulative type. The results are summarized in Table 10.8 blow.

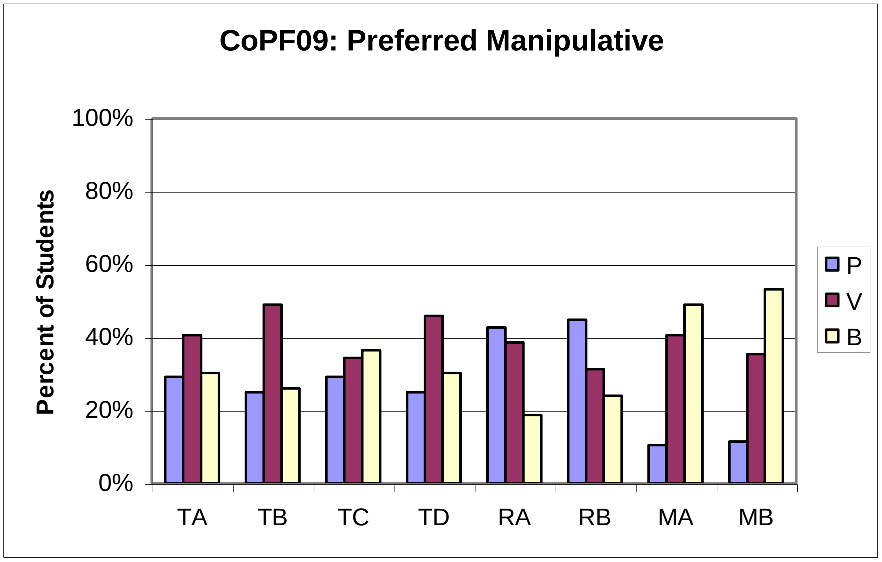


Figure 10.6 Concepts of Physics Fall 2009: Students' survey choices.

**Table 10.8 Concepts of Physics Fall 2009 Survey: Chi-square Goodness of Fit Results**

| **Question** | **Question Description** | **Chi-square** | **p** |
|---|---|---|---|
| TA | Test; Force; Fixed & Movable | $\chi^2$(2, N=96)= 2.3 | .315 |
| TB | Test; Work; Fixed & Movable | $\chi^2$(2, N=96)= 10.6 | **.005** |
| TC | Test; Force; Movable & Double Compound | $\chi^2$(2, N=96)= 0.8 | .666 |
| TD | Test; Work; Movable & Double Compound | $\chi^2$(2, N=96)= 6.7 | **.035** |
| RA | Rental Store; Fixed & Movable | $\chi^2$(2, N=96)= 9.4 | **.009** |
| RB | Rental Store; Movable & Double Compound | $\chi^2$(2, N=96)= 5.4 | **.040** |
| MA | Missed Lab; Force | $\chi^2$(2, N=96)= 23.6 | **<.001** |
| MB | Missed Lab; Work | $\chi^2$(2, N=96)= 25.2 | **<.001** |

As shown in Figure 10.6 above, the virtual manipulative (pulley simulation) was chosen as most useful for three questions, the physical manipulative was chosen as most useful for two questions, and the manipulatives were considered equally useful for three questions. Students' preferences significantly departed from a uniform distribution (an equal number of students selecting each manipulative) on all but two questions, TA and TC. Students more frequently selected the simulation as most useful for the questions in the test context. This preference is especially prominent on questions TB and TD, which asked students about the concept of work. The real toy pulleys were selected as most useful for the questions in the rental store context, and both manipulatives were considered equally useful in the makeup lab context.

Many of these results are not surprising. In the test context, students preferred the computer simulation more frequently for the questions about work than the questions about force. As explained in the literature review, a potential benefit of physical manipulatives is that they allow for kinesthetic experience. Working with the physical pulleys, students can feel the change in required force. However, work is a more abstract concept and is not physically experienced as easily as force. It also makes sense that students most frequently chose the real toy pulleys as most useful in the rental store context since these questions related to using a pulley in real life. In addition, it is not surprising that students rated the two manipulatives as equally useful in the makeup lab context since they would not be the ones experiencing the experiment.

The reasons students provided for their selections were analyzed using a phenomenographic approach (Marton, 1986) to reveal commonly occurring categories. The categories were developed from the collection of reasons for selecting each manipulative type (physical, virtual or both) and are displayed by question in the tables below. Inter-rater reliability on a selection of data was 82%.

Table 10.9 below displays the common categories and prevalence of reasons students gave for choosing the physical manipulative as most effective for the various survey questions. Table 10.10 displays sample student quotes from each category. A common reason given across all survey questions was that the real toy pulleys allowed students to “feel.” This reason was most commonly given to the test questions about force (TA and TC) and the rental store question about simple pulleys (RA). However, students also discussed the ability to feel the work needed in questions TB and TD and in the makeup lab questions. Students also frequently stated that the physical experiment allowed them to see how things worked for themselves. Some students stated that they understood the physical experiment better or gave a general preference for hands-on learning. These categories were most prevalent in the test context.

**Table 10.9 Concepts of Physics Fall 2009 Survey: Reasons for Choosing "Physical"**

| | **TA** | **TB** | **TC** | **TD** | **RA** | **RB** | **MA** | **MB** |
|---|---|---|---|---|---|---|---|---|
| *N* | *28* | *24* | *28* | *24* | *41* | *43* | *10* | *11* |
| Physical lets you feel | 39% | 17% | 21% | 17% | 32% | 4% | 0% | 18% |
| Prefer hands-on learning | 11% | 13% | 7% | 8% | 5% | 9% | 0% | 0% |
| Physical more like real life (friction, errors) | 0% | 0% | 0% | 0% | 29% | 9% | 0% | 0% |
| Visualize better with physical | 0% | 0% | 7% | 0% | 2% | 0% | 0% | 0% |
| Physical easier | 0% | 0% | 4% | 4% | 2% | 2% | 0% | 9% |
| Understand better with physical | 18% | 4% | 18% | 21% | 0% | 9% | 10% | 0% |
| Trust professor's data | 0% | 0% | 0% | 0% | 0% | 0% | 50% | 27% |
| Physical more accurate | 4% | 0% | 0% | 0% | 0% | 0% | 20% | 9% |
| Physical lets you see for yourself | 25% | 25% | 21% | 17% | 22% | 23% | 0% | 0% |

**Table 10.10 Concepts of Physics Fall 2009 Survey: Example Responses (Chose "Physical")**

| **Category** | **Question** | **Examples of Students' Responses** |
|---|---|---|
| Physical lets you feel | TA | "*I think it is obvious which requires less effort when you physically try both options because you really have a chance to feel how much effort it took and which was easier.*" |
| | RA | "*With the real toys, I can actually feel how much effort they need and how hard or easy it is to lift.*" |
| Prefer hands-on learning | TB | "*I learn better doing something hands on.*" |
| | RB | "*Probably real toy again because I like things hands on.*" |
| Physical more like real life (friction, errors) | RA | "*The human element needs to be observed because a computer will not be lifting the dresser.*" |
| | RB | "*Give me a better idea of how each would work under less than ideal situations. Computer has perfect conditions.*" |
| Visualize better with physical | TC | "*The double compound pulley in the experiment with real pulleys show how the string and complexity of the pulley used less of an effort force.*" |
| | RA | "*You will get a more visual idea about how it should work.*" |
| Physical easier | TD | "*Again, by doing this yourself you can easily make a decision, rather than waiting for the computer's answer and still wonder if it is correct.*" |
| | MB | "*Easier to calculate.*" |
| Understand better with physical | TA | "*We were physically doing it, thus we truly understood what was going on.*" |
| | TD | "*Once again, I'm a very visual person. I think the computer one helped a bit, but once I did it myself, it just clicked. I knew it. Had to pull more with the double compound, even though it was easier to move.*" |

| Category | Question | Examples of Students' Responses |
|---|---|---|
| Trust professor's data | MA | *"Since he actually did it, I'm guessing his data is pretty accurate."* |
|  | MB | *"Again, because he actually did the work."* |
| Physical more accurate | MA | *"I would choose this b/c more then likely you will be right and the comp may be wrong."* |
|  | TA | *"There was actually a slight difference for the real pulleys effectiveness. In the real assimilation, but the computer option had the same results basically for 3 types of pulleys."* |
| Physical lets you see for yourself | TB | *"B/c once again you can actually test the pulleys."* |
|  | RB | *"It will help to actually see something being lifted and give you a better idea of what to use."* |

Table 10.11 below displays the categories of common reasons students gave for selecting the simulation as most useful for the various survey questions. Table 10.12 displays example student responses from each category. The most common reason given was that the simulation was more accurate than the physical equipment, reflecting the views students expressed in the wrap-up questions. Another common reason given was that using the simulation was easier than using the physical equipment; this reason was prevalent in the test and rental store contexts but not the makeup lab context. Students also described that the simulation was more useful because it was frictionless or eliminated human error. Interestingly, this category was as prevalent for question RA as for the test context questions. Some students also discussed how the simulation was faster and easier to understand than the physical experiment.

**Table 10.11 Concepts of Physics Fall 2009 Survey: Reasons for Choosing "Virtual"**

|  | **TA** | **TB** | **TC** | **TD** | **RA** | **RB** | **MA** | **MB** |
|---|---|---|---|---|---|---|---|---|
| *N* | *39* | *47* | *33* | *44* | *37* | *30* | *30* | *54* |
| Simulation more accurate | 46% | 43% | 52% | 32% | 57% | 40% | 87% | 35% |
| Simulation easier | 26% | 17% | 15% | 20% | 19% | 30% | 3% | 0% |
| Simulation faster | 5% | 2% | 6% | 5% | 16% | 17% | 0% | 0% |
| Simulations shows ideal conditions (no friction, no human error) | 13% | 13% | 12% | 7% | 14% | 3% | 27% | 9% |
| Simulation easier to understand/clearer data | 3% | 6% | 6% | 0% | 3% | 7% | 10% | 4% |

**Table 10.12 Concepts of Physics Fall 2009 Survey: Example Responses (Chose "Virtual")**

| Category | Question | Examples of Students' Response |
|---|---|---|
| Simulation more accurate | MA | "*The computer's data always seemed to be more exact!*" |
| | RA | "*It allowed me to see the precise force and work done, instead of just estimating.*" |
| Simulation easier | RB | "*Simpler, compound pulleys were hard to make.*" |
| | TA | "*It was easier to get the calculations.*" |
| Simulation faster | RA | "*The real pulleys were time consuming to set up.*" |
| | RB | "*The computer simulation would take less time.*" |
| Simulations shows ideal conditions (no friction, no human error) | MA | "*Because I would still feel better knowing a computer makes less errors than a human.*" |
| | RA | "*There is no friction, so I would know how much work would really have to be done.*" |
| Simulation easier to understand/ clearer data | MA | "*It was less complex than the real pulley data.*" |
| | TB | "*Same as before. It is easier to see on the computer that the work is the same for all types.*" |

Table 10.13 below displays the common categories of reasons students gave for rating the physical and virtual manipulatives as equally useful for the situations presented in the survey. Table 10.14 displays sample student responses from each category. The most common reason for each question was that both manipulatives gave the same results or gave insight into the same concepts. Several students said both experiments were helpful but also listed advantages of the real toy pulleys, simulation or both. The most common combination of advantages was that while the simulation is more accurate, the physical equipment lets you "feel," which pulls from the common reasons given for choosing the physical equipment or simulation. Two new categories emerged for the makeup lab context, where students expressed a desire to compare the data from the two experiments and the belief that their professor would get equally accurate data from both manipulatives.

**Table 10.13 Concepts of Physics Fall 2009 Survey: Reasons for Choosing "Both"**

| | TA | TB | TC | TD | RA | RB | MA | MB |
|---|---|---|---|---|---|---|---|---|
| *N* | *29* | *25* | *35* | *29* | *18* | *21* | *47* | *51* |
| Simulation more accurate, but physical lets you feel | 14% | 0% | 23% | 10% | 11% | 5% | 0% | 0% |
| Both have same results/Show same concept | 62% | 56% | 26% | 21% | 28% | 43% | 38% | 25% |
| Gave advantage of simulation | 21% | 8% | 14% | 10% | 11% | 5% | 6% | 4% |
| Gave advantage of physical | 17% | 12% | 23% | 10% | 11% | 10% | 2% | 2% |
| Trust professor's data | 0% | 0% | 0% | 0% | 0% | 0% | 13% | 4% |
| Can compare data from both | 0% | 0% | 0% | 0% | 0% | 0% | 26% | 10% |

**Table 10.14 Concepts of Physics Fall 2009 Survey: Example Responses (Chose "Both")**

| Category | Question | Examples of Students' Responses |
|---|---|---|
| Simulation more accurate, but physical lets you feel | TC | "*It was good to see the actual number data on the simulation and then feel how much easier a double compound was to pull.*" |
| | RA | "*With the real pulleys I could feel a difference, but with the computers I could actually get specific numbers.*" |
| Both have same results/Show same concept | TA | "*We got about the same data so I don't think it matters.*" |
| | MA | "*The data will be the same w/ the info you are given and find.*" |
| Gave advantage of simulation | TA | "*Both allow you to compare but the real pulleys are hard to set up and get all the data so sometimes it's easier to just see the simulation.*" |
| | RA | "*While the computer model would be more exact, the toy simulation would also give you a good idea of which pulley would be most advantageous.*" |
| Gave advantage of physical | TC | "*Feeling something helps you make a decision, but the computer backs it up.*" |
| | RB | "*The simulation will let you see how they work and the toy will let you experiment with it. The toy will clearly demonstrate their differences.*" |
| Trust professor's data | MA | "*I trust that he got accurate info from both.*" |
| | MB | "*He probably knows more and has good data.*" |
| Can compare data from both | MA | "*I would look over both and compare them, to see how similar or different they were.*" |
| | MB | "*Again, I would have more data to compare from giving me a greater chance for finding a better answer.*" |

The survey data was also analyzed to uncover the question pairs to which the same student gave different answers. As described above, each question specified a context (test, rental store or makeup lab) and a concept (force or work) and/or pulley setups (fixed and movable or movable and double compound). For this analysis, questions were matched on all but one part of the situation description to identify whether changing the concept, pulley setups, or context would cause students to change their answers.

Figure 10.7 below shows the percentage of students who changed their answers when the concept changed from force to work. The comparisons “TA to TB” and “TB to TC” kept the context and pulley setups the same, while the comparison “MA to MB” kept the context the same and did not specify pulley setups. For this set of questions, 21% (for “MA to MB”) to 36% (for “TA to TB”) of students gave different answers to the force and the work questions. Returning to Figure 10.6 above, which displayed the percentage of students who selected each manipulative type for each question reveals that for comparisons “TA to TB” and “TC to TD” students switched from choosing physical or both to choosing virtual. This result is not surprising as the physical experiment tends to give more ambiguous data about work than about force and may better support a physical understanding of force than work. However, for the “MA to MB” comparison, students switched from choosing virtual to choosing physical or both. It is unclear why students made this unexpected transition.

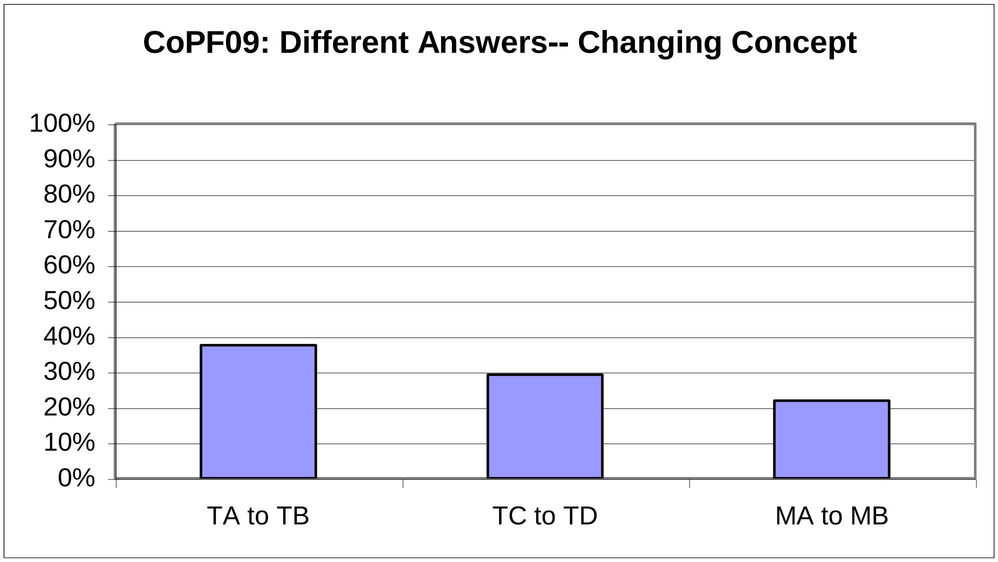


**Figure 10.7 Concepts of Physics Fall 2009: Percentage of students who changed responses when question concept changed.**

Figure 10.8 below shows the percentage of students who changed their answer about the most useful manipulative when the pulley setup changed from simpler pulley systems (fixed and movable) to more complex pulley systems (movable and double compound). Comparisons "TA to TC" and "TB to TD" kept the context and concept the same, while comparison "RA to RB" kept the context the same and did not specify a concept. For this set of questions, 20% to 30% of students gave different answers when the pulley setup changed. Returning again to Figure 10.6 above, for comparisons "TA to TC" and "TB to TD", students seem to have moved from choosing virtual for the simple pulleys to choosing both for the complex pulleys. For the "RA to RB" comparison, students seem to have switched from choosing virtual for the simple pulleys to choosing physical or both for the complex pulleys. This trend is somewhat surprising. One might expect students to prefer to use the computer simulation, which does not require constructing the pulley systems by hand, for the more complex pulley systems. However, the data shows that students selected the physical equipment for the more complex pulley systems.

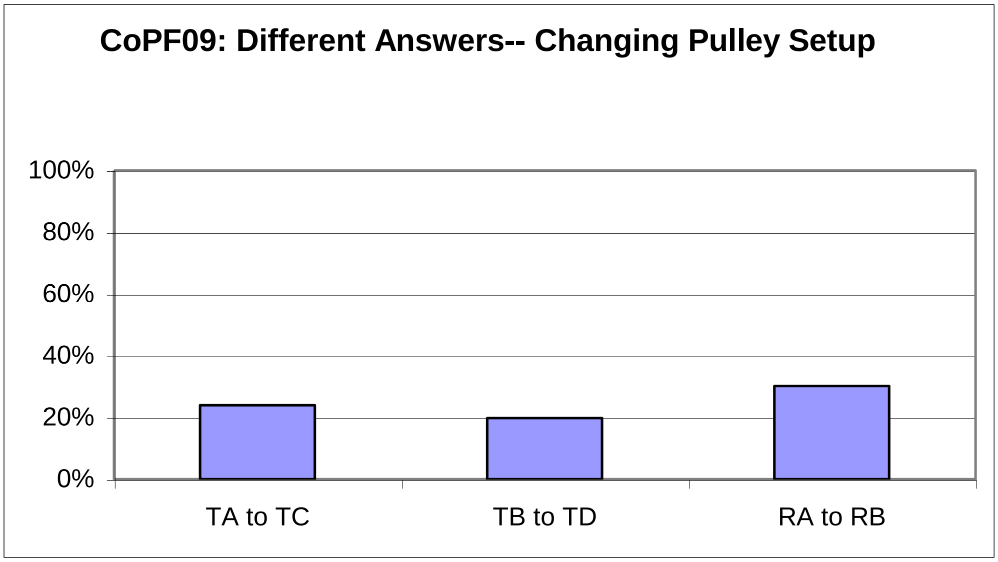


**Figure 10.8 Concepts of Physics Fall 2009: Percentage of students who changed responses when pulley setup changed.**

Figure 10.9 below displays the percentage of students who changed their answers about the most useful type of manipulative when the context of the question changed. Comparisons between the test and rental store context kept the pulley system constant; the test questions specified a concept but the rental store questions did not. Comparisons between the test and makeup lab contexts kept the concept constant; the test questions specified pulley setups but the makeup lab questions did not. It was not possible to match questions between the rental store and makeup lab contexts as one specified a concept while the other specified pulley setups. For this set of questions, 53% to 68% of students gave different answers when the context changed. Returning again to Figure 10.6, for the test to rental store comparisons it appears students moved from choosing virtual or both in the test context to choosing physical in the rental store context. This transition makes sense as test questions often refer to ideal conditions, which could be tested in the simulation, while the rental store context referred to the real-life use of a physical pulley system. For the test to makeup lab comparisons, students seem to have moved from choosing physical or virtual in the test context to choosing both in the makeup lab context. Again, these transitions make sense as students in the makeup lab context would not get the opportunity to have the personal experience of performing either experiment.

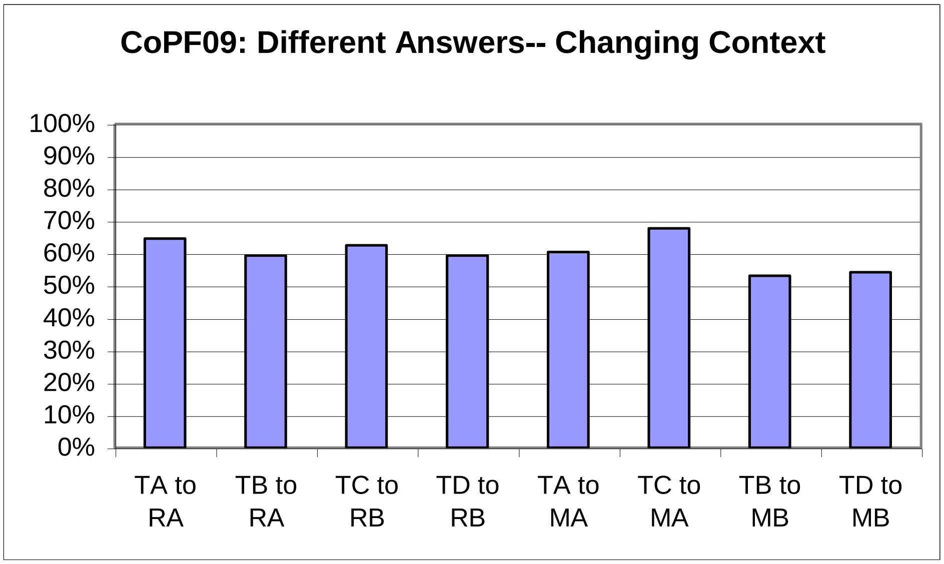


**Figure 10.9 Concepts of Physics Fall 2009: Percentage of students who changed responses when question context changed.**

Comparing across the three types of questions pairs, students were most likely to change their answer when the context changed rather than when the concept or the pulley setup changed. Also, the percentage of individual students who changed their answer was much larger than the change in total percentage of students choosing each manipulative as most useful.  For example, for the “TA to RA” comparison, 65% of students changed their answers between the two contexts.  However, the net difference in the total percentage of students choosing each manipulative was only 14%.

A higher than anticipated percentage of students rated the two manipulatives as equally useful on several of the survey questions.  Some students described that they chose “both equally useful” because they wanted to compare the data from the two types of experiments.  The “both equally useful” option was not meant to offer comparison of the data, but rather to indicate that students would not care which type of experiment or data they were given.  To try to make the intent of the “both” option more clear, this option was changed to state “either would be equally helpful,” and the survey was used with a second group of students in the Physical World in Spring 2010.  The results of the second iteration of the survey are discussed below.

## 10.2 Physical World Spring 2010 (PWS10) Study

Students (N=134) were asked to complete a survey investigating their ideas about experiments performed with physical and virtual manipulatives.  The first eight questions were nearly identical to the survey used in the Concepts of Physics Fall 2009 (CoPF09) implementation.  Again, the students were asked which manipulative they would want to use in a variety of contexts to investigate different concepts or pulley setups.  The contexts, concepts and pulley setups were the same as in the Concepts of Physics implementation and are summarized in Table 10.15 below.  Some students received a version of the survey where the rental store context questions were first, while others received a version where the test context questions were first.

**Table 10.15 Physical World Spring 2010 Survey Questions**

| Question Code | Context | Pulley Systems | Concept |
|---|---|---|---|
| Rental A | Rental store | Fixed & Movable | Not specified |
| Rental B | Rental store | Movable & Double Compound | Not specified |
| Test A | Test | Fixed & Movable | Force |
| Test B | Test | Fixed & Movable | Work |
| Test C | Test | Movable & Double Compound | Force |
| Test D | Test | Movable & Double Compound | Work |
| Makeup A | Missed lab, homework | Not specified | Force |
| Makeup B | Missed lab, homework | Not specified | Work |

The main difference between this survey and the CoPF09 version was the wording of the multiple-choice options. As discussed above, it was not clear whether students were correctly interpreting the meaning of the option "both equally useful." This option was intended to indicate that either the physical or virtual manipulative would be equally useful for the given situation. However, students choosing this option often referred to being able to compare the data from the two manipulatives. To make the intent of this option clearer, it was changed to state "either would be equally helpful."

Figure 10.10 below displays students' choices for the preferred manipulative for each question. A chi-square goodness-of-fit test was used to analyze whether students were equally likely to choose each manipulative type. The results are summarized in Table 10.16 below.

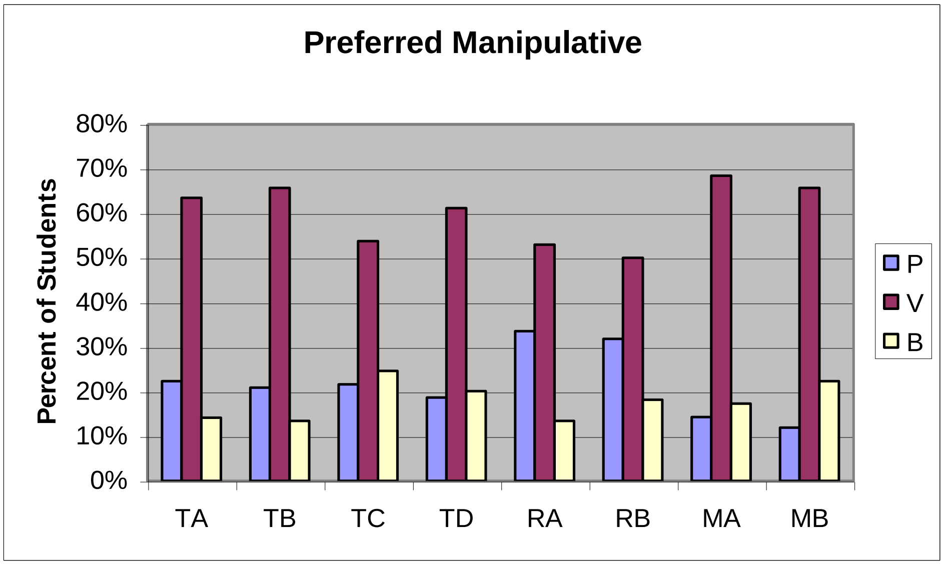


**Figure 10.10 Physical World Spring 2010: Students' survey choices.**

**Table 10.16 Physical World Spring 2010: Chi-square Goodness of Fit Results**

| Question | Question Description | Chi-square | p |
|---|---|---|---|
| TA | Test; Force; Fixed & Movable | $\chi^2(2, N=134)= 56.0$ | <.001 |
| TB | Test; Work; Fixed & Movable | $\chi^2(2, N=134)= 64.2$ | <.001 |
| TC | Test; Force; Movable & Double Compound | $\chi^2(2, N=134)= 25.3$ | <.001 |
| TD | Test; Work; Movable & Double Compound | $\chi^2(2, N=134)= 46.9$ | <.001 |
| RA | Rental Store; Fixed & Movable | $\chi^2(2, N=134)= 31.5$ | <.001 |
| RB | Rental Store; Movable & Double Compound | $\chi^2(2, N=132)= 20.2$ | <.001 |
| MA | Missed Lab; Force | $\chi^2(2, N=133)= 73.9$ | <.001 |
| MB | Missed Lab; Work | $\chi^2(2, N=134)= 65.3$ | <.001 |

The majority of students selected the virtual manipulative in every question. The results were statistically significant for each question. These results are quite different than in the CoPF09 implementation, where students most frequently chose the virtual manipulative for the test context, the physical manipulatives for the rental store context, and both for the makeup lab context. In addition, the percentage of students choosing both manipulatives as equally helpful seldom exceeds 20% in this study, whereas it was much higher in the CoPF09 study.

The reasons students provided for their selections were again coded using a phenomenographic approach (Marton, 1986). The categories from the CoPF09 implementation were used as a base, but new categories were allowed to emerge as well. Inter-rater reliability was 85%.

Table 10.17 below displays the common categories and prevalence of reasons students gave for choosing the physical manipulative as more helpful than the simulation for the various survey questions. No new categories emerged beyond those from the CoPF09 study. Table 10.18 displays sample student quotes from each category. One common reason had to do with the physical manipulative allowing students to “feel.” This was most common for the test questions, especially the test questions about force. Students did still discuss being able to feel in the questions about work. Another common reason given was that the physical experiment was more like real life, possibly by allowing for friction or human errors; this idea was most prominent in the rental store context. Many of the other categories express that some students had a better learning experience from the physical manipulatives. For example, some students discussed a general preference for hands-on learning, others stated they understood better in the physical experiment, and some described being able to visualize better in the physical experiment. A few students reasoned that the physical experiment was more accurate or easier than the simulation.

**Table 10.17 Concepts of Physics Spring 2010 Survey: Reasons for Choosing "Physical"**

| | TA | TB | TC | TD | RA | RB | MA | MB |
|---|---|---|---|---|---|---|---|---|
| *N* | *30* | *28* | *29* | *25* | *45* | *42* | *19* | *16* |
| Physical lets you feel | 17% | 14% | 34% | 12% | 13% | 12% | 0% | 13% |
| Prefer hands-on learning | 13% | 14% | 10% | 12% | 13% | 14% | 0% | 0% |
| Physical more like real life (friction, errors) | 10% | 7% | 3% | 12% | 33% | 36% | 21% | 31% |
| Visualize better with physical | 3% | 11% | 14% | 4% | 7% | 2% | 0% | 0% |
| Physical easier | 10% | 0% | 0% | 0% | 11% | 2% | 0% | 0% |
| Understand better with physical | 17% | 14% | 7% | 8% | 0% | 0% | 11% | 13% |
| Trust professor's data | 0% | 0% | 0% | 0% | 0% | 0% | 11% | 0% |
| Physical more accurate | 0% | 0% | 0% | 0% | 0% | 0% | 26% | 6% |
| Physical lets you see for yourself | 13% | 18% | 21% | 24% | 11% | 12% | 0% | 13% |

**Table 10.18 Physical World Spring 2010 Survey: Example Responses (Chose "Physical")**

| **Category** | **Question** | **Examples of Students' Responses** |
|---|---|---|
| Physical lets you feel | TC | *"You feel the difference in applied force instead of being told."* |
| | RA | *"So that i could feel it for myself, real life action."* |
| Prefer hands-on learning | RB | *"I am hands-on, helps me learn better."* |
| | TB | *"I am a kinesthetic learner, allowing me to actually do the experiment helped make sense of why things happen."* |
| Physical more like real life (friction, errors) | RB | *"Real pulley system will give you a better idea of how the friction affects the system"* |
| | MB | *"Real pulley shows human error & real life example."* |
| Visualize better with physical | TC | *"You get a better picture & feel for it."* |
| | TB | *"Hard to visualize moveable pulley."* |
| Physical easier | RA | *"Because they would be easier to work with."* |
| | TA | *"It's easy to do and experiment's result is obvious."* |
| Understand better with physical | TB | *"Again you understand better if you physically do the experiment."* |
| | MB | *"Because data is more helpful when doing experiment. "* |
| Trust professor's data | MA | *"I trust a professor to do the real experiment accurately."* |
| | MA | *"You visualize that and trust his own data is accurate."* |
| Physical more accurate | MA | *"More accurate to understand when your not there."* |
| | MA | *"Would be more accurate."* |
| Physical lets you see for yourself | TD | *"You are experiencing it for yourself and calculating it on your own."* |
| | RB | *"Just so i can personally see if it works."* |

Table 10.19 below shows the common categories of reasons given for selecting the simulation as more helpful than the physical experiment for the various survey questions. Table 10.20 below displays example student responses from each category. Across the questions, students commonly stated that they would choose the simulation because it was more accurate. Students also commonly reasoned that the simulation was easier or faster to perform than the physical experiment. Some students expressed an understanding that the simulation had ideal conditions because it neglected the effects of friction or eliminated human errors. Additionally, some students stated that the simulation was easier to understand. A few students stated that they were able to test more things with the simulation. This category may have emerged in this implementation because students were asked to investigate a few specific pulley setups and any others they would need to answer the worksheet questions.

**Table 10.19 Physical World Spring 2010 Survey: Reasons for Choosing "Virtual"**

| | **TA** | **TB** | **TC** | **TD** | **RA** | **RB** | **MA** | **MB** |
|---|---|---|---|---|---|---|---|---|
| *N* | *85* | *88* | *72* | *82* | *71* | *66* | *91* | *88* |
| Simulation more accurate | 39% | 31% | 32% | 35% | 21% | 17% | 56% | 56% |
| Simulation easier | 21% | 20% | 25% | 20% | 24% | 30% | 8% | 8% |
| Simulation faster | 9% | 10% | 13% | 11% | 27% | 17% | 1% | 1% |
| Simulation lets you test more things | 1% | 0% | 1% | 0% | 8% | 3% | 0% | 0% |
| Simulations shows ideal conditions (no friction, no human error) | 22% | 16% | 15% | 16% | 13% | 5% | 15% | 8% |
| Simulation easier to understand/ clearer data | 14% | 13% | 17% | 17% | 10% | 14% | 8% | 9% |

**Table 10.20 Physical World Spring 2010: Example Responses (Chose "Virtual")**

| **Category** | **Question** | **Examples of Students' Responses** |
|---|---|---|
| Simulation more accurate | MA | *"It would be more accurate."* |
| | TA | *"More accurate results."* |
| Simulation easier | RB | *"Easier to setup and see results."* |
| | TC | *"There's less hassle in a simulation."* |
| Simulation faster | RA | *"It would be faster to see the differences."* |
| | TB | *"I don't have to set up a pulley system up on a simulation. Much quicker & easier."* |
| Simulation lets you test more things | RA | *"You can change distance, load."* |
| | RB | *"Because you could see which would be better with the higher weight."* |
| Simulations shows ideal conditions (no friction, | TD | *"Takes away human error and other incontrolled variables."* |

| Category | Question | Examples of Students' Responses |
|---|---|---|
| no human error) | MA | *"No friction & other effects."* |
| Simulation easier to understand/ clearer data | TC | *"The computer shows figures and changes very clearly."* |
| | RB | *"Simulation was clear."* |

Table 10.20 below displays the common categories of reasons given by students who stated that either the physical or virtual manipulatives would be equally useful to address the situations in the various survey questions. No new categories emerged beyond those from the CoPF09 study. Table 10.21 below displays example student quotes from each category. The most common reason given for each survey question was that the physical and virtual manipulatives yielded the same results or gave information about the same concept. In the rental store context, a number of students described that while the simulation was more accurate, the physical experiment allowed them to "feel." Other students gave specific examples of advantages of the simulation or physical equipment. A smaller percentage of students discussed being able to compare the data from the two experiments, possibly because of the change in wording in this option.

**Table 10.21 Physical World Spring 2010 Survey: Reasons for Choosing "Both"**

| | TA | TB | TC | TD | RA | RB | MA | MB |
|---|---|---|---|---|---|---|---|---|
| *N* | *19* | *18* | *33* | *27* | *18* | *24* | *23* | *30* |
| Simulation more accurate, but physical lets you feel | 0% | 0% | 0% | 0% | 28% | 13% | 0% | 0% |
| Both have same results/Show same concept | 74% | 33% | 42% | 30% | 39% | 46% | 26% | 23% |
| Gave advantage of simulation | 16% | 6% | 9% | 15% | 6% | 4% | 9% | 7% |
| Gave advantage of physical | 5% | 6% | 12% | 11% | 0% | 4% | 4% | 3% |
| Trust professor's data | 0% | 0% | 0% | 0% | 0% | 0% | 9% | 10% |
| Can compare data from both | 0% | 0% | 0% | 0% | 0% | 0% | 4% | 7% |

**Table 10.22 Physical World Spring 2010 Survey: Example Responses (Chose "Both")**

| Category | Question | Examples of Students' Responses |
|---|---|---|
| Simulation more accurate, but physical lets you feel | RA | *"The computer will give me the right answer, but the toy can give me a real feel."* |
| | RB | *"W/ toys you can feel what you're pulling, w/ simulation you can put in your exact #'s."* |
| Both have same results/Show same concept | TA | *"They both give you accurate results."* |
| | MA | *"The double compound easily demonstrates the lowest effort force in both scenarios."* |

| **Category** | **Question** | **Examples of Students' Responses** |
|---|---|---|
| Gave advantage of simulation | TA | *"Although both give the same results, the simulation is much easier."* |
| | TD | *"It wouldn't make a difference to me, the computer was easier & faster though."* |
| Gave advantage of physical | TC | *"Well it helped to build one first so that i knew what was going on before getting answers and it made the computer simulation easier."* |
| | TD | *"You could feel the differences in pulling."* |
| Trust professor's data | MA | *"They are the professor's data, i'll trust it."* |
| | MB | *"I would assume professor's data would be accurate."* |
| Can compare data from both | MA | *"Because you can compare and contrast the data between the two."* |
| | MB | *"Compare each of them gives more precise answers."* |

As in the analysis for the CoPF09 data, students' responses were analyzed to reveal the pairs of questions to which the same student provided different answers about the type of manipulative that would be most helpful. The same pairings of questions were compared to identify whether changing the concept, pulley setups or context would cause students to change their answers.

Figure 10.11 below displays the percentage of students who changed their answer when the concept changed from force to work. The questions were matched on context (test or makeup lab) and the test questions were additionally matched on pulley setup (fixed and movable or movable and double compound). When the concept changed, 21% (for the "MA to MB" comparison) to 28% (for the "TA to TB" comparison) of students gave different responses about the type of manipulative that would be most useful. Figure 10.10 above displays the percentage of students selecting each option for each survey question. Comparing the responses to these question pairs in Figure 10.11 reveals that the overall percentage of students selecting each option changes much less than the percentage of individual students who changed their answer. In general, the virtual manipulative and "either" were slightly more likely to be chosen as most helpful for the work questions than the force questions. In previous chapters, I have argued that students in fact learn more about work from the virtual experiment than the physical experiment. The survey results suggest students may be aware that the simulation is more beneficial than the physical experiment in particular for the concept of work.

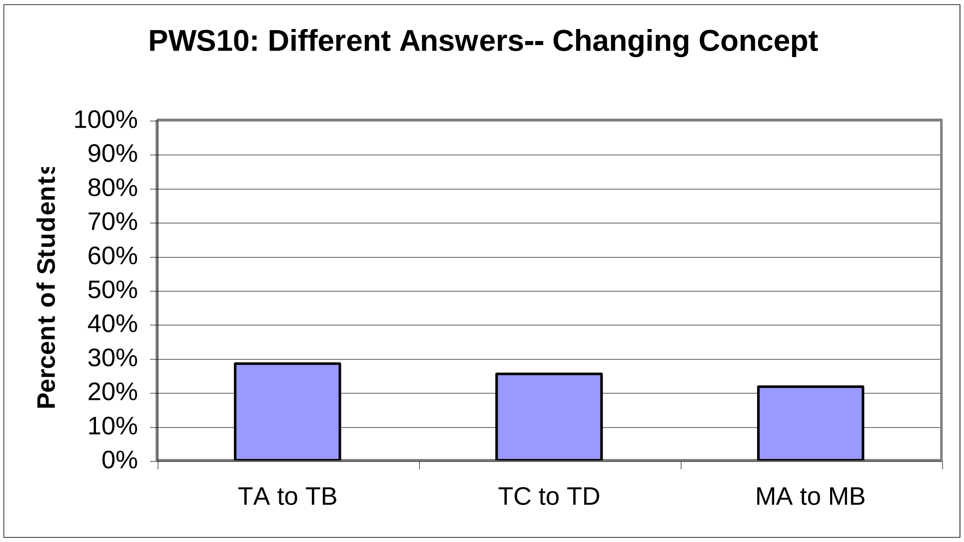


**Figure 10.11 Physical World Spring 2010: Percentage of students who changed responses when question concept changed.**

Figure 10.12 below displays the percentage of students who changed their answer about which manipulative would be most helpful when the pulley setups changed from fixed and movable to movable and double compound. The question pairs are matched on context (test or rental store), and the test questions are additionally matched on concept (force or work). Between 20% and 32% of students changed their answer about which type of manipulative would be most useful when the pulley setup became more complex or harder to construct. Looking at Figure 10.10 above, the percentage of individual students changing their answer is again much larger than the changes in the total percent of students choosing each manipulative type as most helpful. For the “TA to TC” comparison, about 10% fewer students chose virtual for the complex pulleys than the simple pulleys, and about 10% more students chose “either”. The percentage of students selecting “either” also increased by nearly 10% for the complex pulleys for the comparison “TB to TD”. The comparison “RA to RB” shows the same trend but on an even smaller scale. As in the CoPF09 study, it is surprising that students selected physical or either manipulative more frequently for the more complex pulley systems than the simpler pulley systems.

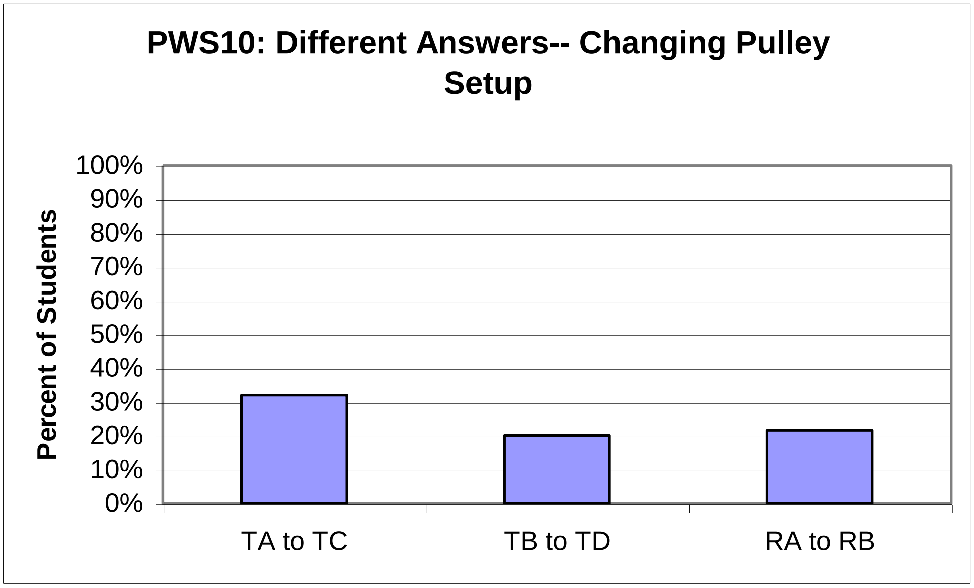


**Figure 10.12 Physical World Spring 2010: Percentage of students who changed responses when pulley setup changed.**

Figure 10.13 below displays the percentage of students who changed their answer about the most helpful manipulative when the question context changed. Comparisons between the test and rental store contexts kept the pulley system constant. The test context questions specified a concept (force or work), but the rental store context did not. Comparisons between the test and makeup lab contexts kept the concept constant. The test context questions specified pulley systems, but the makeup lab context did not. As shown in Figure 10.13 below, between 36% and 49% of students changed their answer when the question context changed. Looking at Figure 10.10 above, the percentage of students who changed their answer again exceeds the change in percentage of students choosing each manipulative type as most helpful. For the test to rental store context comparisons, about 10% more students chose the physical manipulative as most useful in the rental context than in the test context. In the test to makeup lab context comparisons, about 10% less students chose the physical manipulative as most helpful in the lab context than in the makeup lab context. In general, more students chose the virtual manipulative as most helpful or both manipulatives equally helpful.

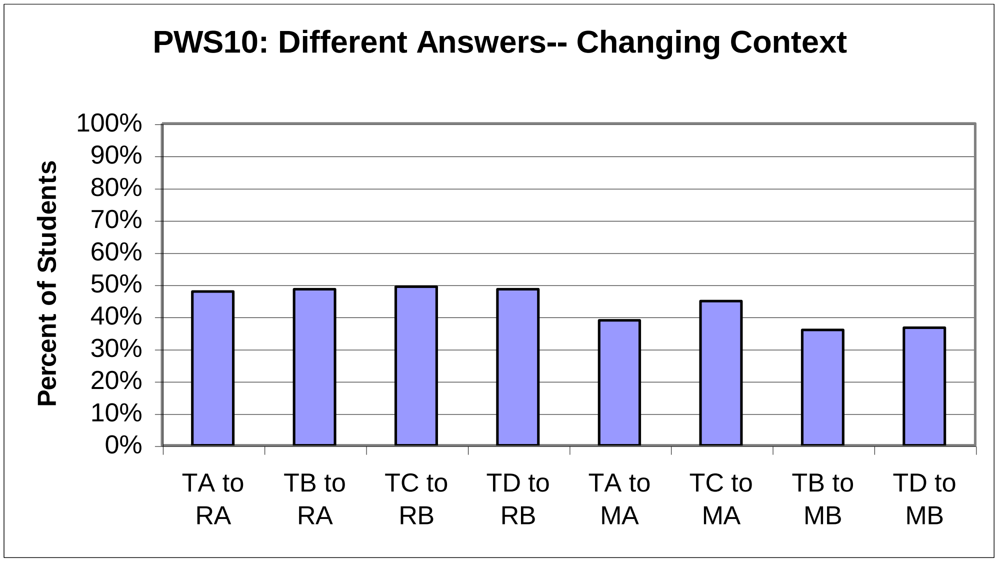


**Figure 10.13 Physical World Spring 2010: Percentage of students who changed responses when question context changed.**

Comparing across the three types of question pairs, students were most likely to change their answer when the context changed. This is the same trend observed in the CoPF09 data. Similar percentages of students changed their answer when the concept or pulley setup changed in both studies. However, students in the CoPF09study were more likely to change their answer when the context changed than were students in the PWS10 study.

Students were asked to respond to two additional survey questions, which explored their ideas about which manipulative better supported their learning and which set of data they trusted more. Students' selections are displayed in Figure 10.14 below. The majority of students selected the virtual manipulative as both better for their learning and more trustworthy than the physical manipulative. Nearly one third of students selected the physical manipulative as offering better support for their learning than the computer simulation, while less than 20% of students chose the physical manipulative as more trustworthy than the simulation.

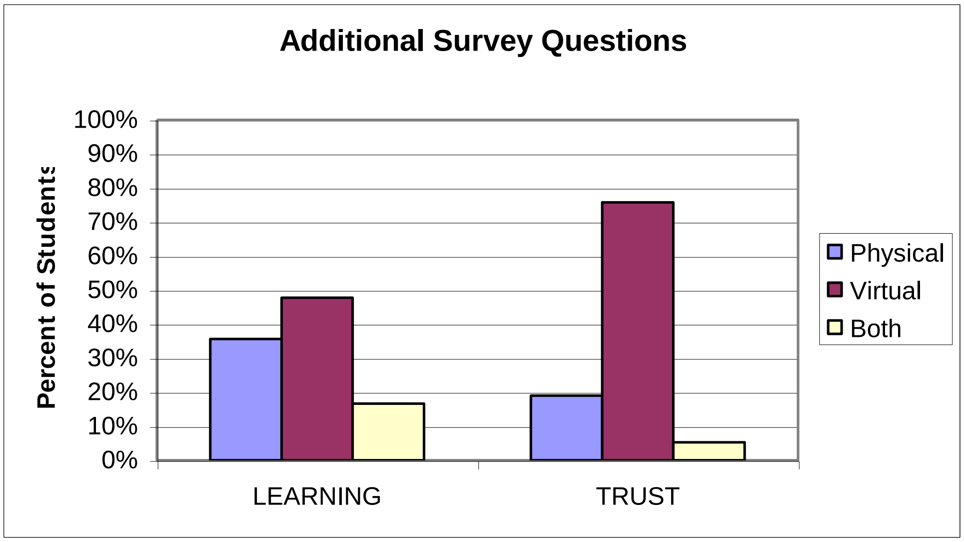


**Figure 10.14 Physical World Spring 2010 Survey: Additional survey questions.**

Students were asked to explain the reasons why they chose a particular manipulative as better for their learning or more trustworthy. A phenomenographic approach (Marton, 1986) was used to find the common categories of reasons given by students selecting each type of manipulative to each question. These results are discussed below.

The common categories of reasons given by students who selected the physical manipulative as better for their learning are displayed in Figure 10.15 below. Example quotes from each category follow in Table 10.23. Some students made statements that expressed that the physical manipulatives were better for learning because they gave the student more control over the experiment. As in the earlier questions, some students again expressed a general preference for hands-on learning. Some students explained that performing the physical experiment would help them to remember better. As in the earlier questions, some students again explained that the physical equipment allowed them to see or feel more of what was going on in the experiment.

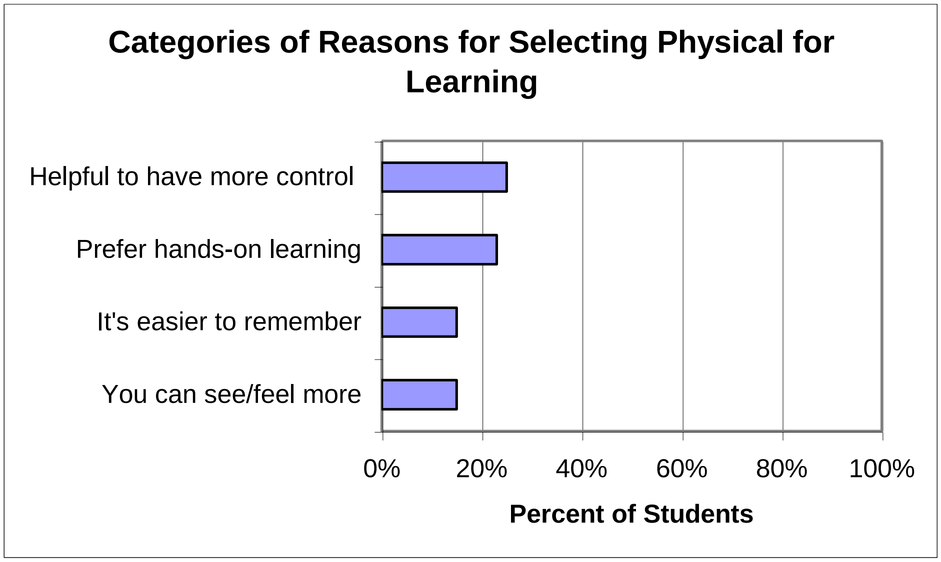


**Figure 10.15 Physical World Spring 2010: Reasons for selecting "physical" for learning.**

**Table 10.23 Physical World Spring 2010: Example Responses (Chose "Physical")**

| **Code** | **Examples of Students' Responses** |
|---|---|
| Helpful to have more control | *"Because if we do experiments, we can create a pulley by our own hands, that's a good way to know pulley system."* |
| | *"I learn better by conducting the experiment."* |
| Prefer hands-on learning | *"Hands-on learning is best. You can experiment more."* |
| | *"I'm a hands-on learner. I get the most out of something by actually doing it."* |
| It's easier to remember | *"Because it goes back to the toy question. It's easier to remember if you actually do the experiment hands on."* |
| | *"The real pulley will leave deep impression to me."* |
| You can see/feel more | *"It gives you a better feel for what is going on."* |
| | *"I understand difference in type of pulleys better when i actually saw how they were setup."* |

Figure 10.16 below displays the common categories of reasons students gave for selecting the virtual manipulative as more supportive of their learning. Example student quotes from each category are shown in Table 10.24, which follows. As in the previous survey questions, many students stated that the simulation was more helpful for their learning because it was more accurate. The other common categories have also occurred in the previous questions; students continued to express that the simulation was helpful because it was easier and faster.

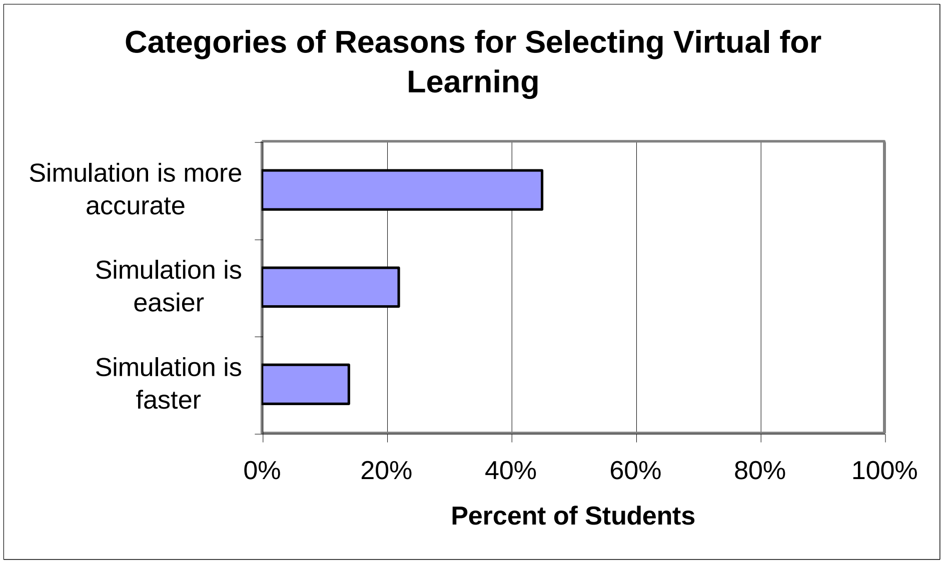


**Figure 10.16 Physical World Spring 2010: Reasons for selecting "virtual" for learning.**

**Table 10.24 Physical World Spring 2010: Example Quotes (Chose "Virtual")**

| Code | Examples of Students' Quotes |
|---|---|
| Simulation is more accurate | *"More accurate, easier to mess up real ones."* |
| | *"I think the computer simulation due to its exact measurements would help me learn best."* |
| Simulation is easier | *"Because do it easier than do it in real life. It's more convenient."* |
| | *"Easier, takes less time & i learn same amount."* |
| Simulation is faster | *"No human error & takes less time so you can focus on results."* |
| | *"Because using computer is quicker."* |

A much smaller percentage of students selected that the physical and virtual manipulatives were both equally helpful for their learning. No major common categories of reasons emerged from the phenomenographic analysis. Half of the students did not provide a reason but rather restated the question. The most common type of response, given by 36% of students, gave an advantage of each manipulative type. These advantages were the same as those given in the previous questions, such as that the simulation was more accurate and the physical allowed the experimenter to "feel."

Figure 10.17 below displays the common categories of reasons students provided for selecting the physical experiment as more trustworthy. Example quotes from each category follow in Table 10.25 below. Less than 20% of the students chose the physical experiment as more trustworthy than the computer simulation. Among students who chose the physical experiment, the majority stated that they trusted the physical experiment because it was more accurate. Other students described that the physical experiment accounted for more factors than the simulation, such as friction. As in the previous question, some students who trusted the physical manipulative expressed that they preferred it over the simulation because they were more in control.

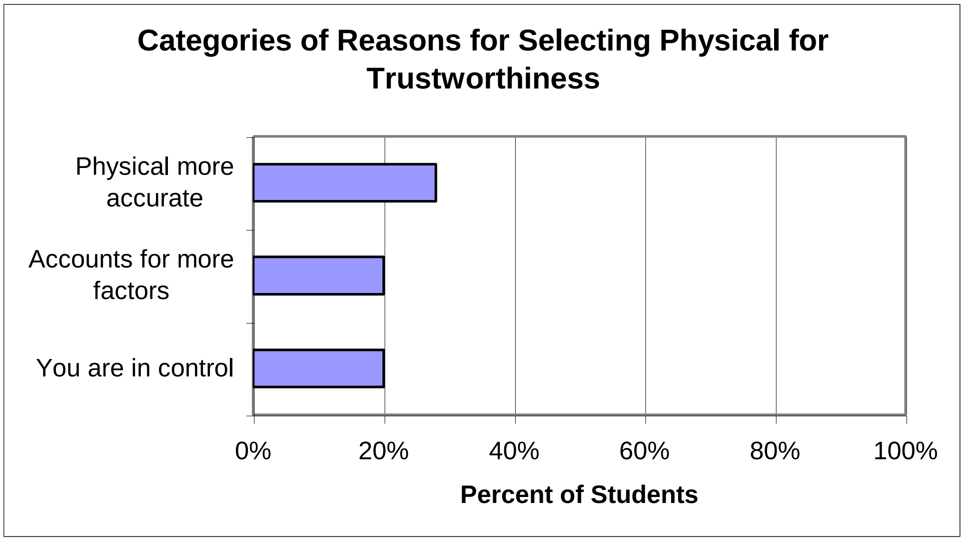


**Figure 10.17 Physical World Spring 2010: Reasons for selecting "physical" for trust.**

**Table 10.25 Physical World Spring 2010: Example Responses (Chose "Physical")**

| **Code** | **Examples of Students' Responses** |
|---|---|
| Physical more accurate | *"Real life never lies."* |
| | *"Computer simulations seem fake to me."* |
| Accounts for more factors | *"It fits to our real life (frictional problem)"* |
| | *"It's real life so the material factors in the friction and other factors."* |
| You are in control | *"You were the one doing the experiment not a computer."* |
| | *"Because you know everything your doing is what is supposed to be done."* |

Figure 10.18 below displays the common categories of reasons given by students who selected the virtual manipulative as more trustworthy than the physical manipulative. Example quotes of each category follow in Table 10.26. An overwhelming majority of students, nearly 75%, selected that they trusted the computer simulation as more trustworthy than the physical experiment. Students' responses fell into two main categories. The majority of students

explained that they would trust the computer simulation because it was more accurate than the physical experiment. This is not surprising, as this reason has appeared in many of the previous survey questions. Some students also expressed that they trusted the virtual manipulative because it was not affected by outside factors like friction.

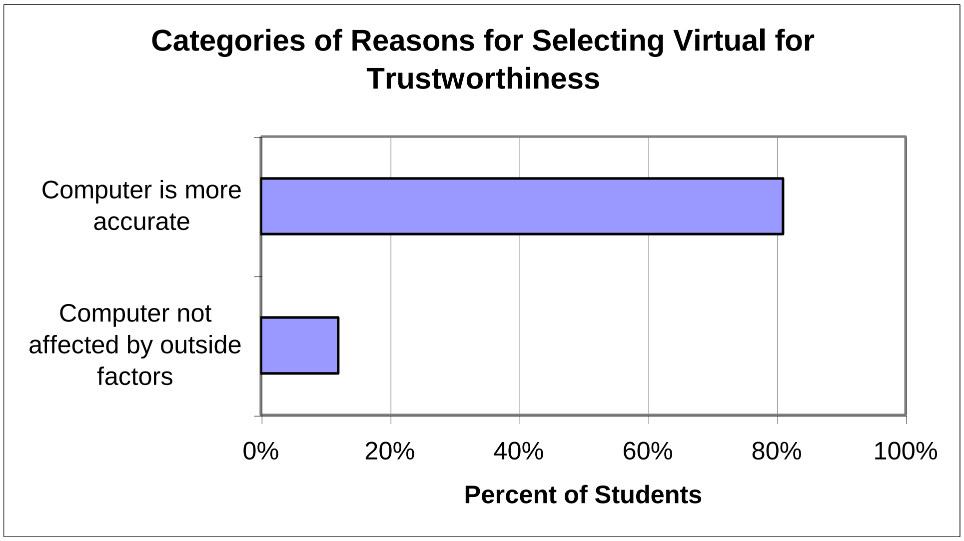


**Figure 10.18 Physical World Spring 2010: Reasons for selecting "virtual" for trust.**

**Table 10.26 Physical World Spring 2010: Example Responses (Chose "Virtual")**

| **Code** | **Examples of Students' Quote Responses** |
|---|---|
| Computer is more accurate | *"The computer can do the measurements and calculations much more accurately than I could."* |
| | *"Maybe we will make some mistakes when we use real pulleys."* |
| Computer not affected by outside factors | *"It's always the same. No outside element to affect it."* |
| | *"No friction, string stretch, other factors."* |

Comparing the reasons given by students who selected the physical or virtual manipulatives as the one to be trusted reveals a difference in opinion about whether it is better to include or exclude the effects of friction in the experiments. In addition, some students expressed the opinion that the physical experiment was more accurate, while a larger percentage of students stated that the simulation was more accurate. Only 6% of students stated that the physical and virtual experiments were equally trustworthy.

## 10.3 Summary and Discussion

In this chapter, I have presented data about students' views of physical and virtual manipulatives from two studies where students performed experiments about pulleys with both physical equipment and a computer simulation. In both studies, students were asked general questions about their feelings about the two experiments. In addition, they were posed specific scenarios and asked which manipulative they would prefer to use in that scenario. In general, the results show that students value the virtual experiment more than the physical experiment.

In the CoPF09 survey, students were asked to compare and contrast the physical and virtual experiments. Students' responses showed that they understood that they were investigating the same ideas in the same way in both experiments, and that those investigations had similar results. Students tended to focus on the "accuracy" of the simulation, but not many students explicitly attributed this to the simulation's ideal conditions. It is not clear whether students knew this and did not express it, or whether they were unsure about how the simulation's data was produced.

In both studies, students were asked to explain which manipulative they trusted more and why. Again, students tended to focus on the accuracy and precision of the simulation and the errors in the physical experiment. The students who chose the physical experiment as more trustworthy discussed that it was a better fit to the real world. It seems the students did not agree about whether it is better to include or exclude the effects of friction in the experiment.

In both studies, students were asked to choose which manipulative they would prefer to use in several scenarios, which included different contexts (test, rental store, missed lab), concepts (force, work) and pulley systems (fixed and movable, movable and double compound). The survey results differed between the two studies, likely because of rewording of the option "both equally useful" to "either would be equally helpful" in the PWS10 study. In the CoPF09 study, students tended to choose the simulation as more useful for the test context, the pulley as more useful for the rental store context, and both as equally useful for the missed lab context. These choices in general made sense as the simulation provides the "textbook answer" one would want in the test context, the physical equipment gives the "real life" experience one would want in the rental store context, and the student would not get the experience of performing either experiment in the missed lab context. However, in the PWS10 study, students chose the simulation as most useful for all questions.

The survey results for each study were analyzed to see how a single student's answers changed when the context, concept or pulley system in the scenario was changed. The results from both studies showed a similar trend. When either the concept or the pulley setup was changed, about one-fifth to one-third of students changed the manipulative they would prefer to use. However, when the context was changed, students were much more likely to change their preferred manipulative. In previous chapters (5 through 8), I have argued that students' learning about work is better supported by the virtual manipulative. However, it appears that the value students attach to physical and virtual manipulatives is more closely tied to the context in which the manipulative would be used.

These questions were designed to provide a glimpse into students' personal epistemologies, or beliefs about knowledge, to address Research Question 3. The physical and virtual manipulatives represent two possible sources of knowledge. Hammer and Elby's (2002) theoretical framework of epistemic resources explains that students may hold different beliefs about knowledge and where knowledge comes from that can be activated in a given situation. These results suggest that, in general, students view the simulation as a more valuable source of knowledge than the physical equipment. While instructors may hope that students' active epistemic resources would be influenced by what supports their learning (i.e. simulation as valuable knowledge source activated to learn about work), it appears that students are more influenced by the context. The context is also a valid "activator" as the specific type of information provided by the physical and virtual manipulatives may be more useful in specific situations. For example, while a double compound pulley may require the least force to lift a load, which can be shown easily in the simulation, information about how to actually build the double compound pulley system is also important, and more likely learned through the physical equipment. It may be useful for instructors and curriculum designers to be aware of the aspects of a problem that prompt students to consider the physical or virtual manipulative as the more valuable source of knowledge.

# CHAPTER 11 - Conclusions and Implications

This research focused on how students' learning about the physics of inclined planes and pulleys was supported by experimentation with physical and/or virtual manipulatives. Several distinct types of studies (i.e. in-class implementations, individual learning/teaching interviews, and surveys) were conducted to address the research questions for this study. In this chapter, I summarize the results of these studies in terms of the research questions raised in Chapter 1. Then, I discuss the implications of these results for future research, curriculum design and instruction.

## 11.1 Research Question 1: What Did Students Learn?

RQ1 asked, "What do students learn from the physical activities and what do they learn from the virtual activities?" In order to tie this question more directly to the data I collected, I divided RQ1 into specific sub-questions. The results to these sub-questions from the pulley and inclined plane studies are discussed below.

### *11.1.1 RQ1a: Worksheet Responses*

The first sub-question asked, "Do students' written responses to data analysis questions differ between the physical and virtual experiments or the physical-virtual and virtual-physical sequences?" This question was addressed by students' responses to the worksheet questions in the in-class implementations of both the pulley and inclined plane curricula. The relevant data analysis for this sub-research question was presented in Chapters 5 (pulleys) and 7 (inclined planes).

#### *11.1.1.1 Pulley Studies*

In the pulley studies, the analysis of students' written responses to the worksheet questions revealed differences between the responses provided by students after performing the physical or virtual experiment and between the physical-virtual (PV) and virtual-physical (VP) sequences for the questions about work and potential energy in each of the three studies (Physical World Spring 2009, Physical World Fall 2009 and Concepts of Physics Fall 2009). The same trend was observed in both the comparison between the responses provided after the first experiment in each sequence (comparison of physical activity versus virtual activity) and between the responses provided after the physical activity in each sequence (comparison of the benefit of the VP sequence to physical activity alone for interpreting physical data). In both cases, students in the VP sequence were more likely to provide responses that aligned with the ideal relationships than were students in the PV sequence. For example, for the question about work, students in the VP sequence were more likely to respond that work was the same or similar across pulley systems, while students in the PV sequence were more likely to respond that work changed across pulley systems. For the question about comparing work and potential energy, students in the VP sequence were more likely to provide a response that adequately addressed the comparison required by the question (i.e. work is similar to potential energy) than were students in the PV sequence, who were more likely to discuss work and potential energy separately or describe them as unrelated.

Thus, it appears that the virtual activity and the VP sequence better supported students' ability to see the ideal relationship that the work required to lift an object should not depend on the machine used to lift it. This is not surprising, since the simulation presented students with idealized data that directly showed this relationship. However, students in the VP sequence seem to have applied this idea to the data from the physical experiment, as well. As described in Section 5.4, this result can be explained by Chinn and Brewer's (1993) framework for possible responses to anomalous data. Since students in the VP sequence were first presented with data from a source they trusted that unambiguously showed that work was constant across pulley systems, they likely interpreted the data from the physical experiment to support their existing theory that work is constant across pulley systems.

It also appears that the virtual activity and VP sequence better supported students' abilities to make comparisons between work and potential energy. When asked to compare work and potential energy, students who had used the manipulatives in the VP sequence were more likely to provide responses that compared work and potential (i.e. work is similar to potential energy), while students who had used the manipulatives in the PV sequence were more likely to discuss work and potential energy separately (i.e. work increased and potential energy stayed the same). As described in Section 5.4, this result can be explained by Schwartz *et al.*'s (2008) theory about dynamic transfer. In the simulation, work was represented as both a number and a bar graph. This graph may provide a "focal point for coordination" to help students make comparisons.

On the other hand, no major difference was observed between students' responses to the questions about force or mechanical advantage in the PV and VP sequences. It is especially surprising that there was no major difference in the force questions for first experiment contrast, between the responses provided after the physical and virtual experiments. One might expect that the physical manipulative would better support students' understanding of force, since it allows them to physically experience the force that must be applied to lift the load.

Overall, the pulley worksheet analysis seems to indicate that the physical and virtual manipulatives equally support students' understanding of force and mechanical advantage. However, the virtual manipulative seems to better support students' understanding of work and potential energy. Students in the VP sequence provide more productive responses about work and potential energy in both the virtual and physical experiments.

#### *11.1.1.2 Inclined Planes Studies*

In the inclined plane studies, the analysis of students' written responses to the worksheet questions revealed differences between the responses provided by students after performing the physical or virtual experiment and between the PV and VP sequences for the questions about work and potential energy in each of the studies (Physical World Spring 2009 and Physical World Fall 2009). Students' responses followed the same trend identified in the pulley study. Specifically, students in the VP sequence were more likely to describe work as constant across different lengths of frictionless inclined planes and were more likely to adequately compare work and potential energy, whereas students in the PV sequence were more likely to talk about work and potential energy separately.

In the PWF09 study, students in the PV sequence provided more physically correct interpretations of how length affected force and mechanical advantage in the physical experiment than students in the VP sequence did. It is interesting that this difference was significant only in the physical data comparison, and not for the comparison between the responses given after the first experiments, where students in the two sequences were looking at different data. It is possible that students are more aware of the length of the inclined plane in the physical experiment because they physically replace shorter boards with longer boards. Also, force and mechanical advantage can be "felt" in the physical experiment, which may help students understand the changes better than the simulation where force is displayed as bar graph.

These results indicate that students may gain a better sense of how changing length affects certain variables from the PV sequence. On the other hand, it may be beneficial to students' understanding of work and potential energy to complete the virtual experiment first.

#### *11.1.1.3 Worksheet Analysis Summary*

Overall, the pulley and inclined plane studies both indicate that the virtual manipulative better supported students' understanding of work and potential energy. The frameworks proposed by Chinn and Brewer (1993) and Schwartz *et al.* (2008) suggest possible explanations for this result. When students perform the virtual experiment first, they are presented with clear data from a source they trust. When they later encounter ambiguous data in the physical experiment, they are likely to interpret that data in light of the results from the virtual experiment. In addition, the bar graph representations in the simulation may support students to make useful comparisons between work and potential energy.

### *11.1.2 RQ1b and RQ1c: Test Performance*

The second sub-question to RQ1 asked, "Do the physical and virtual manipulatives or physical-virtual and virtual-physical sequences provide different support for students' conceptual understanding?" The third sub-question to RQ1 asked, "When students do both physical and virtual activities on the same topic, do they continue to learn in the second activity?" Both of these sub-questions were addressed by students' performance on the conceptual tests in the in-class implementations of the pulley and inclined planes curricula. The relevant data was presented in Chapters 6 (pulleys) and 8 (inclined planes).

#### *11.1.2.1 Pulley Studies*

In each of the three pulley studies, the physical and virtual manipulatives provided equal support for students' understanding of force and mechanical advantage, while the virtual manipulative provided better support for students' understanding of work and potential energy. It is somewhat surprising that the physical and virtual manipulatives equally supported students' understanding of force, since the physical experiment allows students to physically feel the applied force. It is less surprising that the virtual manipulative provided more support for students' understanding of work and potential energy, since the virtual experiment presented students with data from idealized conditions and presented data in multiple representations (i.e. numbers and bar graphs).

Also, across all three pulley studies, the PV and VP sequences provided equal support for students overall learning and each of the concepts (force, work and mechanical advantage). Thus, it appears that the sequence in which students used the manipulatives did not affect their performance on the post-test.

In the Physical World Spring 2009 and Physical World Fall 2009 pulley studies, students' total scores and work/energy sub-scores increased significantly from mid-test to post-test. This indicates that students' continued to learn about work and potential energy in the second experiment. The graphs of students' performance in the PV and VP sequences reveal that it was specifically the students in the PV sequence who continued to learn about work and potential energy in the second experiment, which was the virtual activity. This is not surprising since it appears that the virtual manipulative provided better support for students' conceptual understanding of work and potential energy. This trend did not occur in the Concepts of Physical Fall 2009 pulley study; in fact, students' work and energy scores did not significantly improve at any point. This is likely because the students were less prepared to learn about work as the study occurred very early in the semester. Students did not appear to continue to learn about force or mechanical advantage in the second activity in any of the pulley studies.

#### *11.1.2.2 Inclined Plane Studies*

In the Physical World Spring 2009 (PWS09) inclined plane study, students performed only a subset of activities (changed length and height or length and surface of inclined plane) and used only the physical or virtual manipulatives. Thus, this study only allows comparison of the physical and virtual manipulatives. Students force and mechanical advantage sub-scores were similar for both activities and both manipulatives. However, students who had performed the Length/Height activities with the virtual manipulative performed better on the work and potential energy questions than students in all three other treatments. Students in the Length/Height Virtual treatment only saw frictionless trials in the simulation. However, students in the Length/Friction Virtual treatment saw trials both with and without friction, but performed similarly to the students who had used the physical equipment. This result suggests that seeing any trials with friction, whether in the physical or virtual experiment, may negatively affect students' ability to answer questions about work in idealized conditions, as were asked on the conceptual test.

In the Physical World Fall 2009 (PWF09) study, students explored the effect of changing length, height and friction and used both the physical and virtual manipulatives. The physical and virtual manipulatives and PV and VP sequences appeared to offer equal support for all concepts (force, work and mechanical advantage). In addition, students only appeared to learn about any of the concepts during the first experiment in each sequence.

#### *11.1.2.3 Test Analysis Summary*

In the pulley studies, the virtual manipulative appeared to better support students' understanding of work and potential energy than the physical manipulatives did. However, in the PWF09 inclined plane study, the physical and virtual manipulatives appeared to offer equal support for students' understanding of work and potential energy. The PWS09 inclined plane study suggests a possible explanation for this difference. In the PWS09 inclined plane study, students used the virtual manipulative to perform two subsets of activities. One group of students changed only the length and height of the inclined plane in the simulation; these students only observed trials with a frictionless surface. Another group of students changed the length and surface of the inclined plane in the simulation; these students saw frictionless trials in the length experiment, but trials with friction in the surface experiment. The students who had seen only frictionless trials performed better on the conceptual test questions about work and potential energy than the students who had seen trials both with and without friction did.

In the pulley study, the simulation only presented students with data from a frictionless experiment. However, frictional effects were always present in the physical experiment. Thus, it is possible that the difference in support offered by the virtual manipulative for the work/energy sub-score between the pulley and inclined plane studies is tied to the presence of friction in the inclined plane simulation. It appears that the frictionless trials do help students to learn about the idealized nature of work and potential energy. However, students appear to need additional scaffolding to interpret the difference between the trials with friction and the trials without friction productively.

### *11.1.3 RQ1 Summary*

Across all the studies, it appears the main difference in support offered by the physical and virtual manipulatives occurs for students' understanding of work and potential energy. While one may have expected that the physical manipulative would better support students' understanding of force since the physical experiment allows students to physically experience the force being applied, that claim is not supported by these studies. It is less surprising that the physical and virtual manipulatives offered equal support for students' understanding of mechanical advantage, since it seems plausible that each manipulative could offer distinct support for this topic. For example, mechanical advantage is closely tied to applied force, which students can physically feel in the physical experiment. However, it is also an abstract concept, which may be better supported by the multiple representations (i.e. numbers and bar graphs) in the simulation.

In both the pulley and inclined plane studies, the virtual manipulative and VP sequence appeared to offer better support for students' discussion of work and the comparison between work and potential energy in their worksheet responses. As previously discussed, this may be due to the unambiguous data presented by the simulation or more support for dynamic transfer provided by the simulation. However, the virtual manipulative only appeared to offer better support than the physical manipulative for students' conceptual understanding of work and potential energy as measured by the conceptual tests in the pulley studies and not in the inclined plane studies. This result appears to be tied to the presence of friction in the inclined plane simulation, and indicates that students need additional scaffolding to consider the differences between real world (i.e. with friction) and idealized (i.e. frictionless) conditions.

Hammer (2000) suggested that different contexts might activate different conceptual resources. This theory can shed some light on the results of Research Question 1. It is possible that performing the virtual experiment first activates a resource related to "changing input does not affect output", which is useful for understanding why changing the type of pulley or the length of inclined plane does not affect the work needed to lift the load. Once this resource has been activated in the virtual experiment, students may continue to use it to reason about work in the virtual experiment.

## 11.2 Research Question 2: How Did Students Learn?

RQ2 asked, “Do the environments created by the physical and virtual manipulatives offer different support for dynamic transfer? What features of each environment create the support? Can the support offered by one environment be recreated in the other?” This question was addressed by the individual learning/teaching interviews, and the relevant data analysis was presented in Chapter 9. As described in Section 2.5.2.4, Schwartz *et al.* (2008) described the various ways that an environment can support a learner to develop new concepts, a process they call dynamic transfer. The environment can support dynamic transfer by allowing for distributed memory, providing alternative interpretations and feedback, providing candidate structures, and serving as a focal point for coordination. I used this framework to explore how the physical and virtual manipulatives supported students’ learning processes in the one-on-one interviews where students used either the physical or virtual manipulatives to learn about inclined planes.

The results of this analysis indicated that the virtual manipulative provided better support for dynamic transfer than the physical manipulative did. I found the virtual manipulative to offer each type of support through several different features. For example, the virtual manipulative allowed for distributed memory by performing calculations and allowing students to backtrack by quickly rerunning forgotten trials. It provided alternative interpretations and feedback by providing immediate feedback about abstract quantities (i.e. work) and allowing students to explore a frictionless environment. The virtual manipulative provided candidate structures through the list of possible physics topics to explore, and the bar graphs appear to provide a candidate structure for making comparisons. Finally, the simulation provided a focal point for coordination through the bar graphs, which helped students to consider several quantities at a time, and the frictionless trial, which helped students coordinate their ideas of idealized conditions and the real world. On the other hand, I only documented the physical manipulative to provide support through alternative interpretations and feedback by allowing students to experience tactile feedback.

RQ2 asks whether the support offered by one manipulative could be recreated in the other manipulative. My analysis also revealed several ways in which each environment failed to support dynamic transfer, so I also discussed ways in which those failures could be overcome. Both the physical and virtual environments should be altered to support students to record data between trials. In the in-class implementations, this was done by providing students with explicit instructions about what data to record and a pre-designed data table in which to record the data. In addition, the simulation could be altered to store previous trials, which would allow the students to record their data in the simulation itself. In order to allow the physical experiment to provide better alternative interpretations and feedback, the physical equipment provided could be supplemented with additional low-friction surfaces. In addition, students could be provided with support to identify causes of and avoid inaccurate measurements. The candidate structure provided by the list of possible science concepts to explore present in the simulation could be reproduced in the physical environment. In the simulation, students appeared to need support to understand the physical meaning of variables (i.e. how friction connects to surface), which would help the simulation to be both a better candidate structure and focal point for coordination. It appears that even with these suggested changes, the simulation would still offer better support for dynamic transfer than the physical experiment.

## 11.3 Research Questions 3: What Did Students Think About Their Learning?

RQ3 asked, “Do students view the information from physical and virtual manipulatives differently? Is there evidence that different epistemic resources are activated by the two contexts?” I collected data with two types of surveys to address this research question. In one type of survey, students were asked to discuss the physical and virtual experiments in terms of their similarities, differences and relative trustworthiness. In the second type of survey, students were asked to identify whether they would prefer to use the physical or virtual manipulative to collect specific types of information (i.e. what pulley to rent or how to answer a question about pulleys on a test). Survey data was collected in the Concepts of Physics Fall 2009 (CoPF09) pulley study and in the Physical World Spring 2010 (PWS10) study, after students had completed the pulley experiments. The relevant data analysis was presented in Chapter 10.

In general, the results showed that students valued the virtual experiment over the physical experiment. Students tended to focus on the accuracy or precision of the simulation and the possible errors in the physical experiment. This led many students to describe the simulation as more trustworthy than the physical experiment. The few students who chose the physical experiment as more trustworthy than the simulation described it as a better fit to the real world. In the CoPF09 study, students more frequently chose the simulation as the most useful for collecting information to answer test questions, the physical manipulatives as most useful for collecting information about what pulley to rent to lift furniture, and both manipulatives as equally useful for getting information about a laboratory experiment they missed. On the other hand, students in the PWS10 study chose the simulation as most useful in all the situations. One possible reason for this difference is that the wording for the "both" option on the survey was worded "both equally useful" in the CoPF09 study and "either would be equally helpful" in the PWS10 study.

The physical and virtual manipulatives represent two possible sources of knowledge. Hammer and Elby's (2002) theoretical framework of epistemic resources explains that students may hold different beliefs about knowledge and where knowledge comes from that can be activated in a given situation. These results suggest that, in general, students view the simulation as a more valuable source of knowledge than the physical equipment. I analyzed how students' responses about which manipulative was more useful changed between the different situations (with different pulley systems, different contexts and different physics concepts). Students most frequently changed their response about which manipulative would be most useful when the context changed (e.g. from asking about test questions to asking about renting a pulley to use). This suggests that students' epistemic resources may be activated by the context more than by the physics concept in question.

### *11.3.4 Research Question Summary*

Research Question 1 focused on *what* students learned from the physical and virtual experiments. Across all the studies, it appears the main difference in support offered by the physical and virtual manipulatives occurs for students' understanding of work and potential energy. In both the pulley and inclined plane studies, the virtual manipulative and VP sequence appeared to offer better support for students' discussion of work and the comparison between work and potential energy in their worksheet responses. This result may be due to the unambiguous data presented by the simulation or more support for dynamic transfer provided by the simulation. However, the virtual manipulative only appeared to offer better support than the physical manipulative for students' conceptual understanding of work and potential energy as measured by the conceptual tests in the pulley studies and not in the inclined plane studies. This result appears to be tied to the presence of friction in the inclined plane simulation, and indicates that students need additional scaffolding to consider the differences between real world (i.e. with friction) and idealized (i.e. frictionless) conditions.

Research Question 2 focused on *how* students learned from the physical and virtual experiments. Students' interactions with the physical and virtual manipulatives were analyzed through the lens of the support each offered for dynamic transfer. This analysis indicated that virtual manipulatives offered more support for dynamic transfer than the physical manipulatives did.

Research Question 3 asked what students *thought about* their learning when using the physical and virtual manipulatives. Students' responses to survey questions indicate that they value the virtual experiment over the physical experiment. Students selected the virtual experiment as more trustworthy than the physical experiment and tended to chose the virtual experiment as more useful than the physical manipulative to collect various types of information.

## 11.4 Implications

In this final section, I describe implications for future research as well as for curriculum design and instruction. Due to the specific context (physics concepts related to inclined planes and pulleys) and population (students enrolled in introductory physics courses) studied, the applicability of these results to other contexts and populations must be explored.

### *11.4.1 Implications for Future Research*

Several directions for future research can be identified based on these results. This study uncovered potentially both context (i.e. pulley versus inclined plane) and concept (i.e. force versus work) dependency to the answer to which manipulative (physical or virtual) is more beneficial to students' learning. Thus, it appears that more research is needed to explore how other contexts and concepts are supported by experimentation with physical and virtual manipulatives.

This research only assessed a small subset of the possible ways in which the physical and virtual manipulatives could support students learning. Thus, more research is needed to explore whether there are other ways in which one manipulative is more beneficial for students' learning. For example, one could explore whether students who used the simulation to perform experiments about pulleys could later construct a physical pulley system as well as students who had performed experiments with physical pulleys.

The discrepancy in how the physical and virtual manipulatives support students' understanding of work and potential energy between the pulley and inclined plane studies suggests more research is needed to explore why this difference occurred. One possible explanation is that the pulley simulation was entirely frictionless, whereas students did explore friction in the inclined plane simulation. If this were identified as the reason, more research would be needed to explore how to effectively scaffold students to understand the difference between idealized (i.e. frictionless) and real world (with friction) conditions.

Students' responses to the survey questions indicated that students enrolled in a conceptual-based introductory physics course tended to trust data from the simulation more than data from the physical experiment. It would be interesting to investigate whether this finding holds for other populations, as well. It seems possible that younger students, who may have more or less exposure to virtual worlds, may have different ideas about the simulation's data. On the other hand, students with more experience with scientific investigations may be more likely to question the reliability of the simulation's data.

In addition, students' responses to the survey questions suggest more research is needed to explore students' understanding of how the simulations produce data. Students frequently discussed the accuracy of the simulation, but they less frequently attributed the accuracy to the absence of friction in the simulation. It is not clear whether they knew the simulation was frictionless but did not discuss it, or if they did not know why the simulation's results matched the "textbook" results better than the physical experiment. It would be interesting investigate whether understanding of how the simulation produces data varies between college students and middle school students.

Another venue for future research is how to best interweave experiences with physical and virtual manipulatives in order to optimize the advantages of each and help students to see connections between them. For example, these results suggest a potentially useful manipulative sequence. Since the physical and virtual manipulatives typically provided equal support for students' understanding of force, students could start by exploring force with the physical manipulatives. Next, since the virtual manipulative typically provided more support for students' understanding of work and potential energy, students could explore those concepts with the virtual manipulative. Then, students could return to the physical experiment to explore work and potential energy in real world conditions (i.e. with friction). This sequence seems promising because it supports students to make useful interpretations of physical data, which is a goal of much science instruction. It seems likely that performing the virtual experiment first will activate a resource for thinking about "changing the input does not affect the output", which is useful for reasoning about how changing the simple machine does not affect the work required to lift a load to a constant height. However, further research is necessary to investigate the usefulness of this sequence.

### *11.4.2 Implications for Curriculum Design and Instruction*

These results suggest that the traditional wisdom that students learn best from physical experiments is not necessarily true. Students' worksheet responses and test performance were typically equivalent or better when students had performed experiments with virtual manipulatives as when they had performed experiments with traditional physical equipment. In addition, it seems that virtual manipulatives are better able to provide students with support for dynamic transfer, or the creation of new concepts. Thus, it may be useful for curriculum designers and instructors to spend more of their efforts designing learning experiences that make use of virtual manipulatives.

These results support the claim made by Klahr, Triona and Williams (2007) that, since physical experiments do not appear to support students' understanding more than virtual experiments, teachers should look at other factors related to physical and virtual manipulatives as the basis for choosing which to use. The researchers point out that virtual manipulatives are generally easier to develop, implement and manage than physical manipulatives. In addition, virtual experiments take less time, space and effort and are easy to duplicate. Thus, in some cases, virtual experiments seem to offer more advantages than physical experiments.

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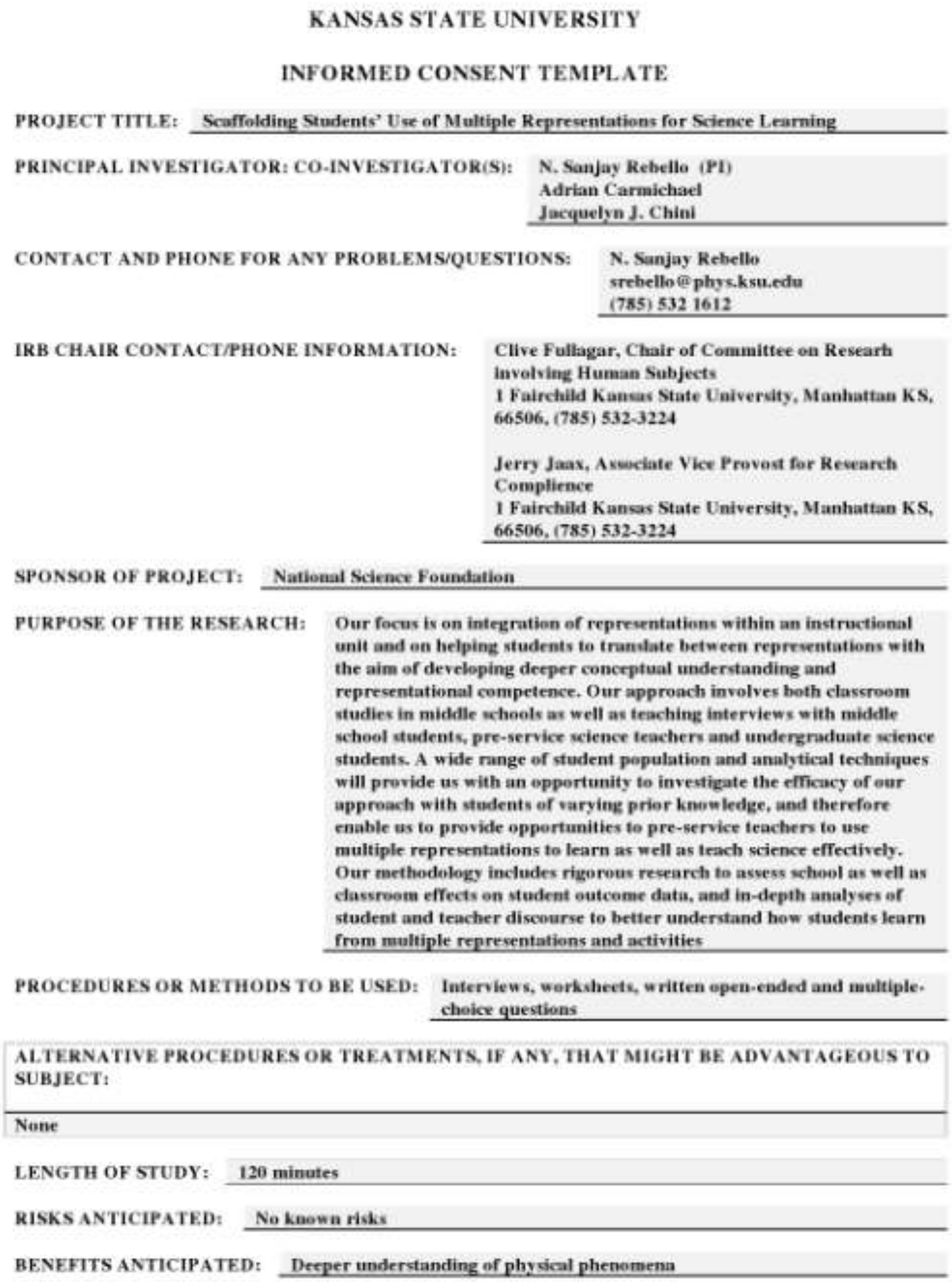
# Appendix A - Interview Consent Form

The Informed Consent Form given to students who participated in the inclined plane teaching/learning interviews is included in the following pages. Students read and signed the form before beginning the interview.



## KANSAS STATE UNIVERSITY

## INFORMED CONSENT TEMPLATE

**PROJECT TITLE:** Scaffolding Students' Use of Multiple Representations for Science Learning

**PRINCIPAL INVESTIGATOR: CO-INVESTIGATOR(S):** N. Sanjay Rebello (PI)
Adrian Carmichael
Jacquelyn J. Chini

**CONTACT AND PHONE FOR ANY PROBLEMS/QUESTIONS:** N. Sanjay Rebello
srebello@phys.ksu.edu
(785) 532 1612

**IRB CHAIR CONTACT/PHONE INFORMATION:** Clive Fullagar, Chair of Committee on Researh involving Human Subjects
1 Fairchild Kansas State University, Manhattan KS, 66506, (785) 532-3224

Jerry Jaax, Associate Vice Provost for Research Complience
1 Fairchild Kansas State University, Manhattan KS, 66506, (785) 532-3224

**SPONSOR OF PROJECT:** National Science Foundation

**PURPOSE OF THE RESEARCH:** Our focus is on integration of representations within an instructional unit and on helping students to translate between representations with the aim of developing deeper conceptual understanding and representational competence. Our approach involves both classroom studies in middle schools as well as teaching interviews with middle school students, pre-service science teachers and undergraduate science students. A wide range of student population and analytical techniques will provide us with an opportunity to investigate the efficacy of our approach with students of varying prior knowledge, and therefore enable us to provide opportunities to pre-service teachers to use multiple representations to learn as well as teach science effectively. Our methodology includes rigorous research to assess school as well as classroom effects on student outcome data, and in-depth analyses of student and teacher discourse to better understand how students learn from multiple representations and activities

**PROCEDURES OR METHODS TO BE USED:** Interviews, worksheets, written open-ended and multiple-choice questions

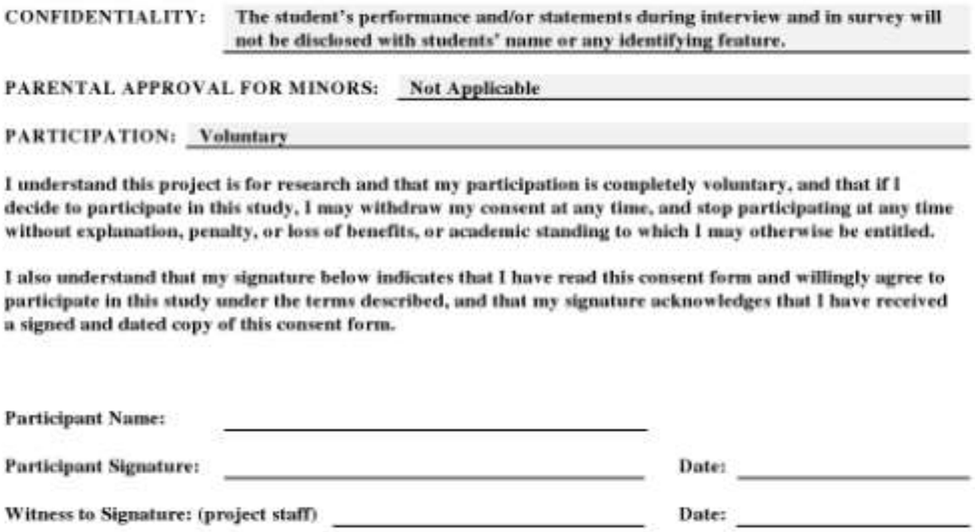
**ALTERNATIVE PROCEDURES OR TREATMENTS, IF ANY, THAT MIGHT BE ADVANTAGEOUS TO SUBJECT:**

None

**LENGTH OF STUDY:** 120 minutes

**RISKS ANTICIPATED:** No known risks

**BENEFITS ANTICIPATED:** Deeper understanding of physical phenomena



**CONFIDENTIALITY:** The student's performance and/or statements during interview and in survey will not be disclosed with students' name or any identifying feature.

**PARENTAL APPROVAL FOR MINORS:** Not Applicable

**PARTICIPATION:** Voluntary

**I understand this project is for research and that my participation is completely voluntary, and that if I decide to participate in this study, I may withdraw my consent at any time, and stop participating at any time without explanation, penalty, or loss of benefits, or academic standing to which I may otherwise be entitled.**

**I also understand that my signature below indicates that I have read this consent form and willingly agree to participate in this study under the terms described, and that my signature acknowledges that I have received a signed and dated copy of this consent form.**

**Participant Name:** ______________________

**Participant Signature:** ______________________ **Date:** ____________

**Witness to Signature: (project staff)** ______________________ **Date:** ____________

## ADDENDUM TO INFORMED CONSENT FORM

I hereby state that:

- I have read, understood and signed the **Kansas State University, Informed Consent (Template)** Form.
- I have agreed to complete an activity for a total duration of **two hours in Fall 2008** in connection with the study described in the **Kansas State University, Informed Consent (Template)** Form.
- I understand that I will be compenstated **$25 for my participation in the two hour long interview**.
- I understand that information collected from me during this activity, including any demographic information will be kept strictly confidential by the Project Staff. Videotapes and audiotapes of the activity, and their transcripts will be stored in a secure place, and will be destroyed after the publication of the research resulting from this study.
- I understand that I will not be identified either by name or by any other identifying feature in any communication, written or oral, pertaining to this research.
- I understand that if I wish to withdraw from the study at any time, either before a scheduled interview, during an interview or after an interview I can do so without explanation, penalty, or academic standing that I may otherwise be entitled.
- I understand that by signing this form, I have consented to have information learned from me during the process to be used by the Project Staff in their research and any resulting publications.

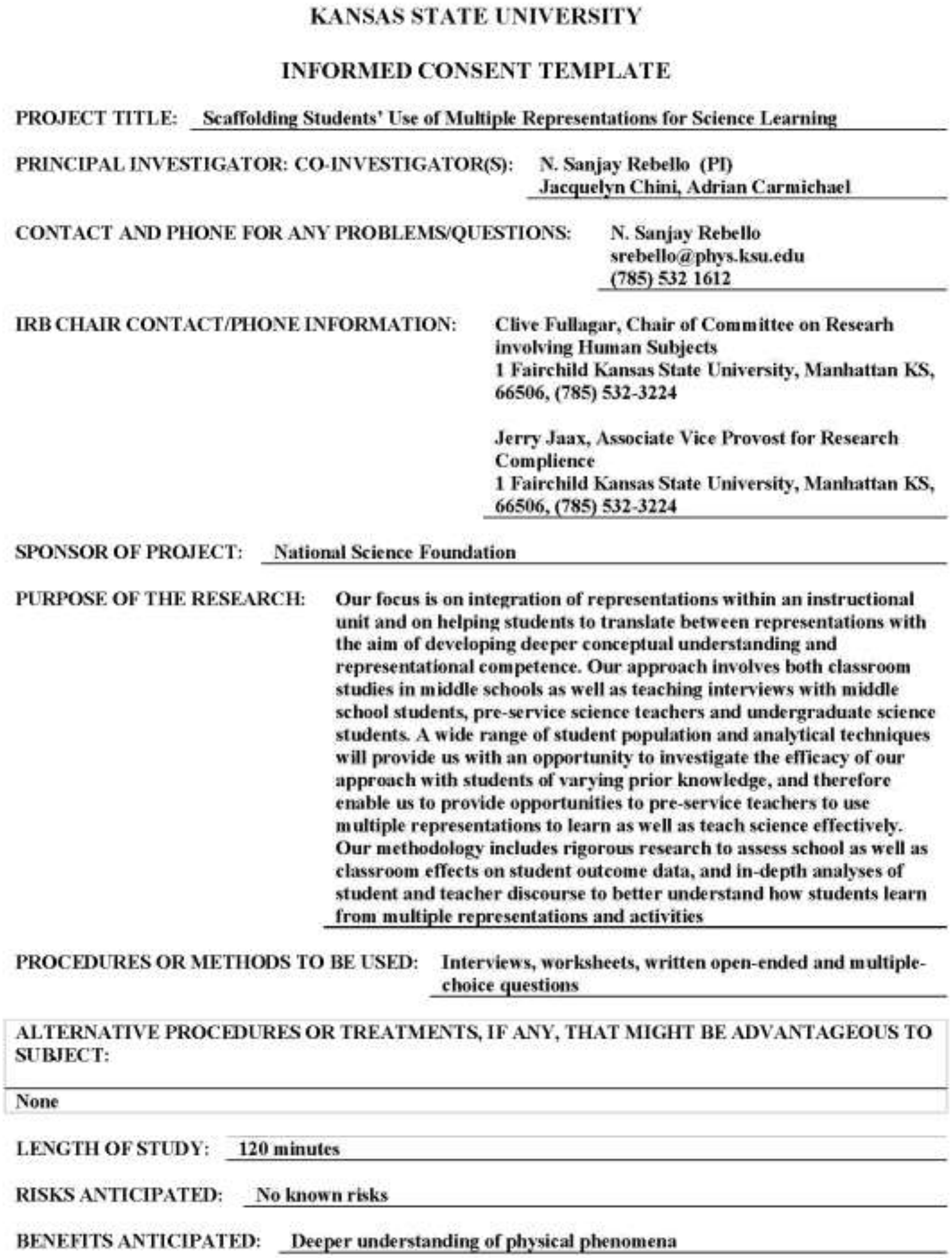
Participant Name: ______________________________________________

Participant Signature ______________________ Date: ______________

Witness to Signature ______________________ Date: ______________
(Project Staff)

# Appendix B - Concepts of Physics Fall 2009 Consent Form

During the CoPF09 form, students were asked whether they would agree to be audio- or video-recorded while they worked through the activities. Students indicated their preferences on the Informed Consent Form, which is included in the following pages.



## KANSAS STATE UNIVERSITY

## INFORMED CONSENT TEMPLATE

**PROJECT TITLE:** Scaffolding Students' Use of Multiple Representations for Science Learning

**PRINCIPAL INVESTIGATOR: CO-INVESTIGATOR(S):** N. Sanjay Rebello (PI)
Jacquelyn Chini, Adrian Carmichael

**CONTACT AND PHONE FOR ANY PROBLEMS/QUESTIONS:** N. Sanjay Rebello
srebello@phys.ksu.edu
(785) 532 1612

**IRB CHAIR CONTACT/PHONE INFORMATION:** Clive Fullagar, Chair of Committee on Researh involving Human Subjects
1 Fairchild Kansas State University, Manhattan KS, 66506, (785) 532-3224

Jerry Jaax, Associate Vice Provost for Research Complience
1 Fairchild Kansas State University, Manhattan KS, 66506, (785) 532-3224

**SPONSOR OF PROJECT:** National Science Foundation

**PURPOSE OF THE RESEARCH:** Our focus is on integration of representations within an instructional unit and on helping students to translate between representations with the aim of developing deeper conceptual understanding and representational competence. Our approach involves both classroom studies in middle schools as well as teaching interviews with middle school students, pre-service science teachers and undergraduate science students. A wide range of student population and analytical techniques will provide us with an opportunity to investigate the efficacy of our approach with students of varying prior knowledge, and therefore enable us to provide opportunities to pre-service teachers to use multiple representations to learn as well as teach science effectively. Our methodology includes rigorous research to assess school as well as classroom effects on student outcome data, and in-depth analyses of student and teacher discourse to better understand how students learn from multiple representations and activities

**PROCEDURES OR METHODS TO BE USED:** Interviews, worksheets, written open-ended and multiple-choice questions

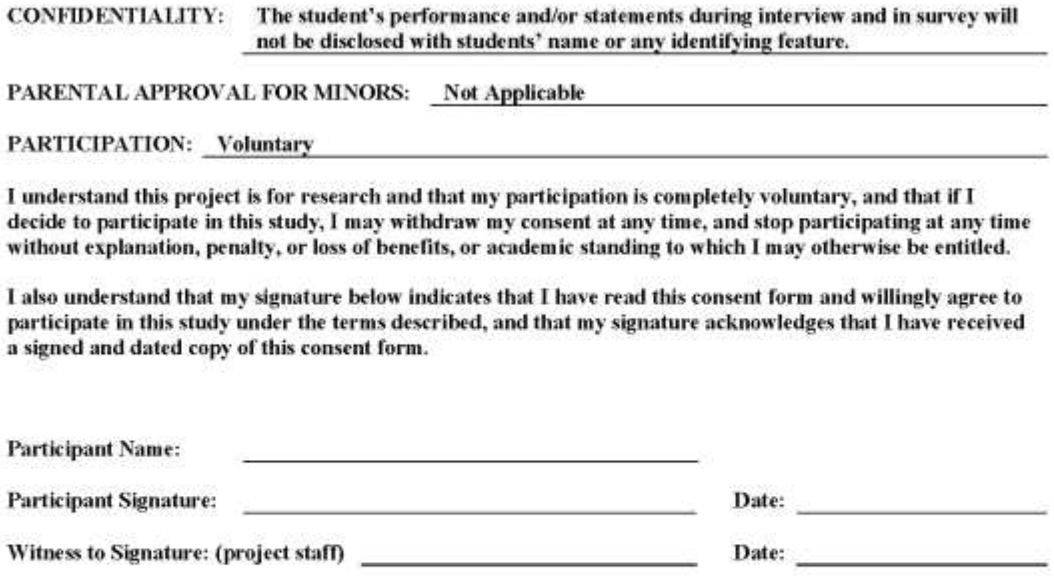
**ALTERNATIVE PROCEDURES OR TREATMENTS, IF ANY, THAT MIGHT BE ADVANTAGEOUS TO SUBJECT:**

None

**LENGTH OF STUDY:** 120 minutes

**RISKS ANTICIPATED:** No known risks

**BENEFITS ANTICIPATED:** Deeper understanding of physical phenomena



CONFIDENTIALITY: **The student's performance and/or statements during interview and in survey will not be disclosed with students' name or any identifying feature.**

PARENTAL APPROVAL FOR MINORS: **Not Applicable**

PARTICIPATION: **Voluntary**

**I understand this project is for research and that my participation is completely voluntary, and that if I decide to participate in this study, I may withdraw my consent at any time, and stop participating at any time without explanation, penalty, or loss of benefits, or academic standing to which I may otherwise be entitled.**

**I also understand that my signature below indicates that I have read this consent form and willingly agree to participate in this study under the terms described, and that my signature acknowledges that I have received a signed and dated copy of this consent form.**

**Participant Name:** ____________________

**Participant Signature:** ____________________ **Date:** ____________

**Witness to Signature: (project staff)** ____________________ **Date:** ____________

## ADDENDUM TO INFORMED CONSENT FORM

I hereby state that:

- I have read, understood and signed the **Kansas State University, Informed Consent Template** Form.
- I have agreed that as part of the project described on the attached Informed Consent Template Form, data will be collected in **PHYS 106** ***Concepts of Physics*** from time to time in **Fall 2009.**
- I understand that information collected from me during this class, including any demographic information will be kept strictly confidential by the Project Staff. Videotapes and audiotapes of the activity, and their transcripts will be stored in a secure place, and will be destroyed after the publication of the research resulting from this study.
- I understand that I will not be identified either by name or by any other identifying feature in any communication, written or oral, pertaining to this research.
- I understand that if I wish to withdraw from the study at any time, I can do so without explanation, penalty, or loss of benefits, or academic standing that I may otherwise be entitled.
- I understand that by signing this form, I have consented to have information learned from me during the process to be used by the Project Staff in their research and any resulting publications.
- By signing below, I consent to the following forms of data collection during this project (check all that are applicable)

☐ Video taping of the activity

☐ Audio taping of the activity

Participant Name: ____________________________________________________

Participant Signature _________________________ Date: _________________

Witness to Signature __________________________ Date: __________________

(Teaching Assistant or Project Staff member)

# Appendix C - PWS09 Pulley Test

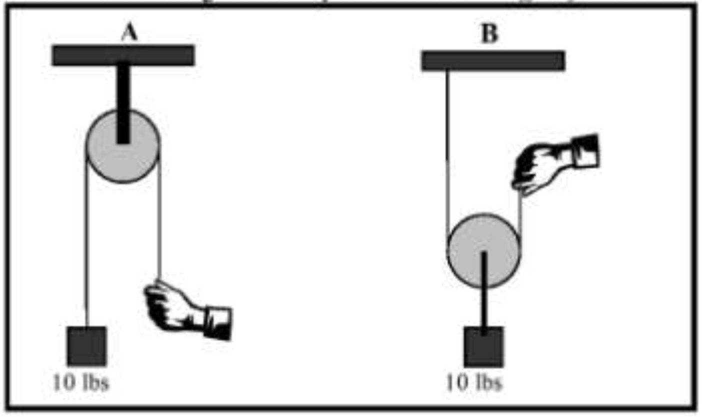
Several versions of a conceptual multiple-choice test about pulleys were used in the studies presented in this dissertation. The test on the following pages was used in the Physical World Spring 2009 (PWS09) pulley study.

**NAME (Please Print):** ______________________________

## Pulley Post-Test

**Instructions**: In the multiple choice questions, select only *one* letter to indicate your answer.

**1**) In which of the following cases will you need a *smaller effort force* to lift the load?



A.) Pulley A

B.) Pulley B

C.) Both A & B are equal

D.) Not enough information

**2a**) You used a fixed pulley to lift a watermelon to your tree house. If you changed it to a movable pulley…

the *distance* pulled would:

*Circle one*:

A.) Increase

B.) Decrease

C.) Stay the same

D.) Not enough information to decide

and the *effort force* required would:

*Circle one*:

A. Increase

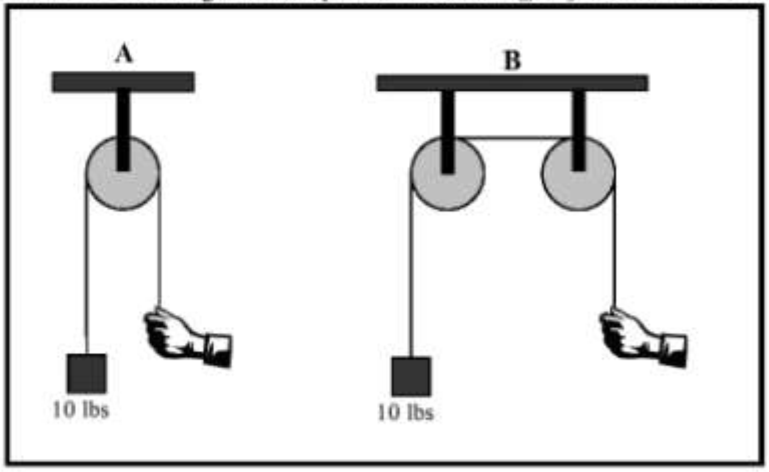
B. Decrease

C. Stay the same

D. Not enough information to decide

**2b**) Explain your reasoning about both the *distance* and *effort force* in this question.

**3**) In which of the following cases will you need a *smaller effort force* to lift the load?



A.) Pulley A

B.) Pulley B

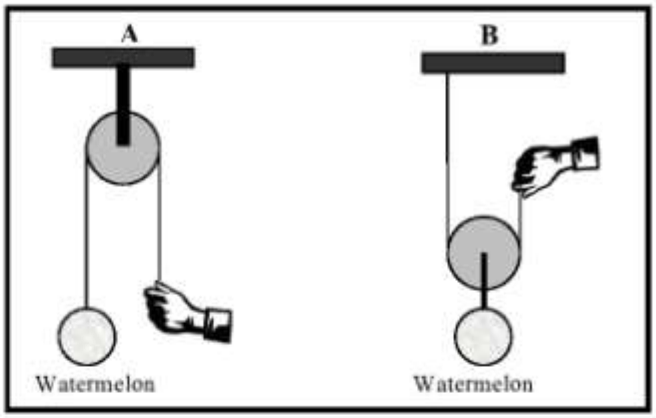
C.) Both A & B are equal

D.) Not enough information

**4**) Explain the trade off between *effort force* and *distance* when using a movable pulley.

Post-Test (Purple) 2

**6a**) You use pulley A to lift a watermelon to your tree house. If you used a pulley B instead to lift the same watermelon…



the *effort force* needed would:

*Circle one*:

A.) Increase

B.) Decrease

C.) Stay the same

D.) Not enough information to decide

and the *work* done would:

*Circle one*:

A.) Increase

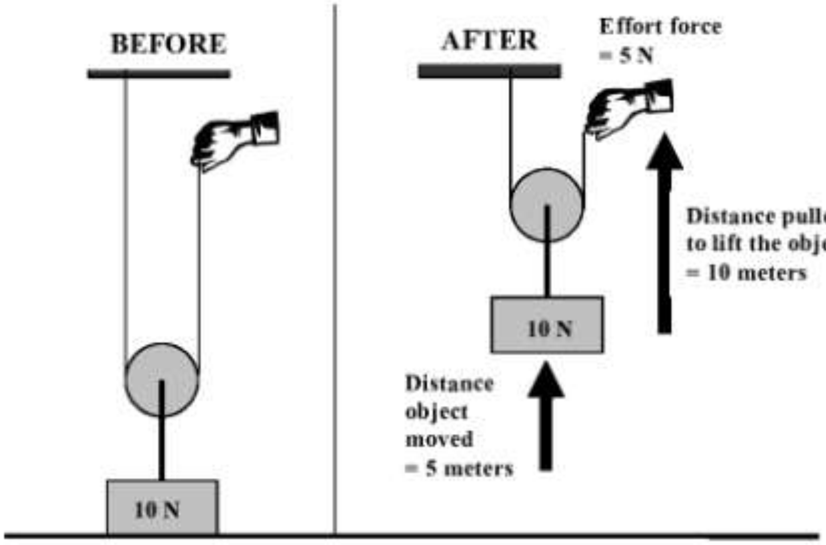
B.) Decrease

C.) Stay the same

D.) Not enough information to decide

**6b**) Explain your reasoning about both *effort force* and *work* in this question.

7) Below are before and after pictures of a load being lifted with the help of a pulley. Calculate *work* using the information from the picture below:



Do your calculations below. <u>Clearly show any formulas AND values that you use</u>.

8) Jacob is using a fixed pulley to separately lift two boards of the exact size and mass up to two different heights. He lifts one board 10 meters and then lifts the second board 20 meters. When lifting the board 20 meters, Jacob is doing _____________ work as/than when lifting the first board 10 meters high?

A.) more

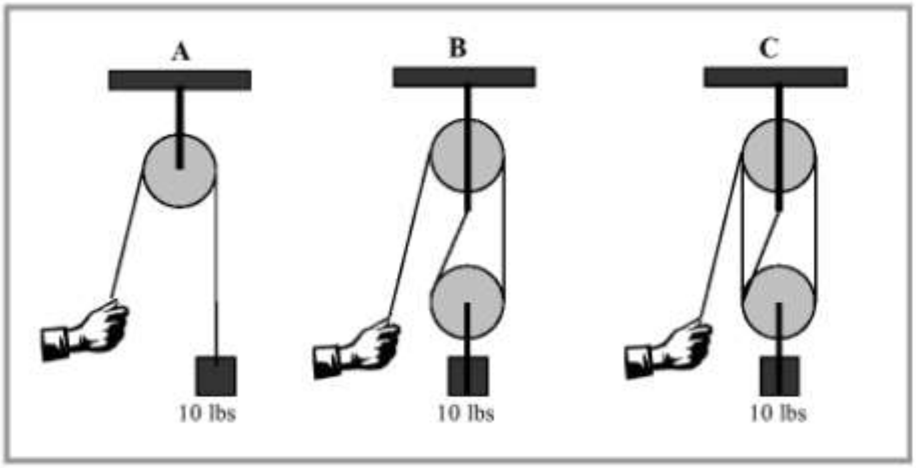
B.) less

C.) the same amount of

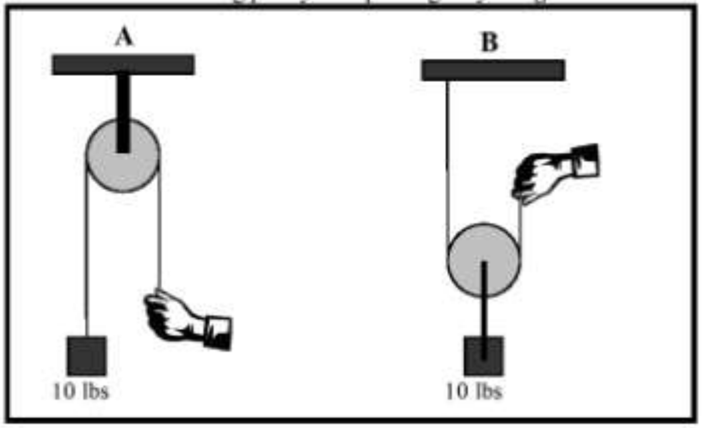
D.) not enough information to decide

**9)** Alice is using pulley set-up A, Brenda is using B, and Carl is using C. What can you tell about the *work needed* to lift the load by each of them, if friction is not a factor?

A.) Alice (using pulley system A) is doing more work
B.) Brenda (using pulley system B) is doing more work
C.) Carl (using pulley system C) is doing more work
D.) The work done in all three situations is the same



**11**) Which one of the following pulley set-up will give you a *greater mechanical advantage*?



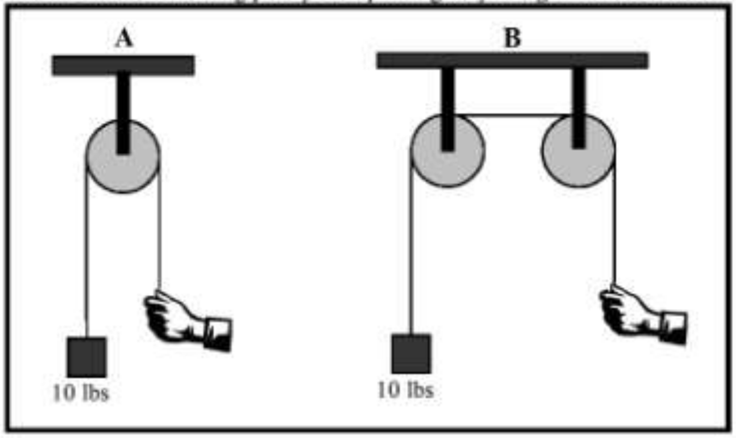
A.) Pulley A

B.) Pulley B

C.) Both A & B are equal

D.) Not enough information

**12**) Which one of the following pulley set-up will give you a *greater mechanical advantage*?



A.) Pulley A

B.) Pulley B

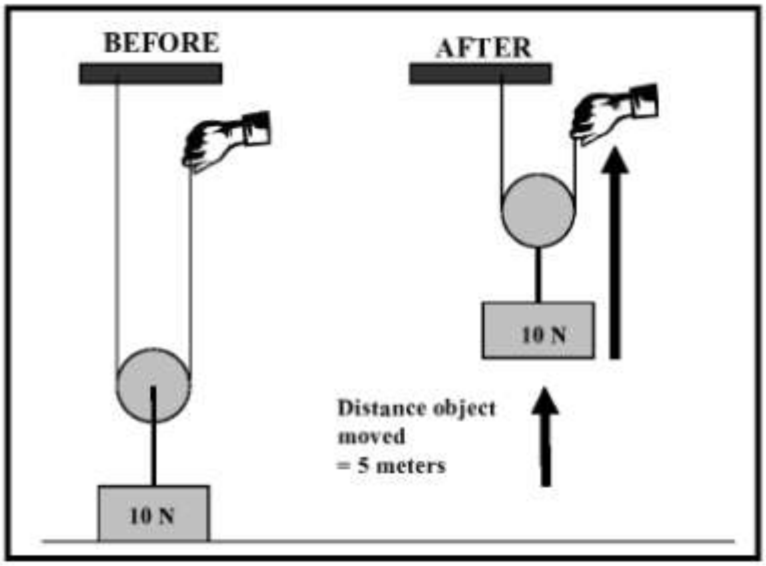
C.) Both A & B are equal

D.) Not enough information

**13**) You use a movable pulley to lift a watermelon to your tree house. How does the work you do lifting the watermelon compare to its potential energy once lifted?

A.) The work is *more* than the potential energy
B.) The work is *less* than the potential energy
C.) The work and potential energy are the same
D.) Not enough information

**14a**) What is the *potential energy* of the block in each before and after the load is lifted?



A) Potential energy before = 0 J Potential energy after = 5 J

B) Potential energy before= 10 J Potential energy after = 10 J

C) Potential energy before = 0 J Potential energy after = 50 J

D) Potential energy before= 10 J Potential energy after = 50 J

**14b**) Explain your reasoning for your answer to question 14a) above

# Appendix D - Test Validity Study

Two post-docs and two graduate students were recruited to assess the validity of the pulley and inclined plane conceptual tests. The participants were asked to describe what each question was to testing and to comment on whether any questions were unrelated to the test domain. Tables D.1 and D.2 below displays the information they provided.

**Table 11.1 Pulley Test Validity Information**

| Q# | Concept | Inclined Planes | Post-doc1 | Post-doc2 | Student1 | Student2 |
|---|---|---|---|---|---|---|
| | | | (thru out need to assume pulley is massless) | | | |
| 1 | Force | Single fixed; Single movable | Force | Force; MA | Newton's 2$^{nd}$ Law, static situation; Force/Tension | Tension in strings |
| 2 | Force | Single compound; No pulley | Force | Force; MA | Newton's 2$^{nd}$ Law, static situation; Force/Tension | Tension in strings |
| 3a | Distance | Single fixed; Single movable | distance | Force | Fixed vs. movable pulleys; Geometry | Distance pulled vs. change in height |
| 4 | Force | Single fixed; Single movable | Force | | Newton's 2$^{nd}$ Law; Force/Tension | Work energy theorem |
| 5 | Force | Single fixed: well-oiled vs. sticky | Effect of friction on required force | Force; Friction | Friction | Work done to overcome friction |
| 6 | Force | Single fixed; Single compound | Force | Force; MA | Newton's 2$^{nd}$ Law; Force/Tension | Division of tension |
| 7 | Force | Single fixed; Two single fixed; Single movable; Double compound | Force | Force; MA | Newton's 2$^{nd}$ Law; Force/Tension | Types of pulleys |

| Q# | Concept | Inclined Planes | Post-doc1 | Post-doc2 | Student1 | Student2 |
|---|---|---|---|---|---|---|
| 8a | Force | Single fixed; Single movable | Force | Force and work | Newton's 2nd Law; Force/Tension | work |
| 8b | Work | Single fixed; Single movable | Work | | Work= F * d | Work-energy theorem |
| 9 | Work | Single movable | Work | Force and work | W= F * d | Work-energy theorem |
| 10 | Work | Single compound; No pulley | Work | Force and work; MA | W= F * d | Work-energy theorem |
| 11 | Work | Single fixed: well-oiled vs. sticky | Effect of friction on work required | Force and work; Friction | Friction; W= F * d | Work done to overcome friction |
| 12 | Work | Single fixed | Work | Force and work | W= F * d | Work-energy theorem |
| 13 | Work | Single fixed; Single compound; Double compound | Work | Force and work; MA | Force/tension; W= F * d | Work-energy theorem |
| 14 | MA | One single fixed; Two singled fixed, Single movable; Double compound | MA | MA | MA; Force/ Tension | MA |
| 15 | MA | One single fixed; Two single fixed | MA | MA | MA; Force/ Tension | Division of tension in strings |
| 16 | MA | Single fixed; Single movable | MA | Gravitation; Force vs. work; MA | MA; Force/ Tension | Division of tension in strings |
| 17 | PE | Single compound | PE | Gravitation; Force | ΔPE = mgh | PE |
| 18 | PE | Single fixed; Single compound | PE | Gravitation; Force; MA | ΔPE = mgh | PE |
| 19 | W/PE | Double compound (well-oiled) | Work energy theorem | Gravitation; Force; MA | W= ΔPE = mgh when friction is negligible | Work-energy does not equal work when friction is |

| Q# | Concept | Inclined Planes | Post-doc1 | Post-doc2 | Student1 | Student2 |
|---|---|---|---|---|---|---|
| | | | | | | involved |
| 20 | W/PE | Double compound (needs to be oiled) | Work energy theorem & friction | Gravitation; Force; MA | W > ΔPE when friction is not negligible | Work-energy does not equal work when friction is involved |

### Table 11.2 Inclined Plane Test Validity Information

| Q# | Concept | Inclined Planes | Post-doc1 | Post-doc2 | Student1 | Student2 |
|---|---|---|---|---|---|---|
| 1 | Force | Different length, same height | Force/work | Gravitation; Force vs. work | Greater slope requires greater force or ramps reduce the amount of force required for lifting | Work/energy theorem or force as a vector |
| 2 | Force | Ramp; Lifting | Force/work | Gravitation; Force vs. work; MA | Greater slope requires greater force | Work/energy theorem or force as a vector |
| 4 | Force | Same length, different height | Force/work | Gravitation; Force vs. work | Greater slope -> greater force and slope = rise/run | Work/energy theorem or force as a vector |
| 5 | Force | Smooth surface; Rough surface | Friction/force | Gravitation; Force vs. work; Normal force and friction | Friction requires additional force to be overcome and rough surfaces have more friction | Work done to overcome friction |
| 6 | Force | Different length and height | Force/work | | Force proportional | Force as a vector |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  | (proportional) |  |  | to slope; Slope = rise/run |  |
| 8a1 | Force | Different length, same height | Force/work | Gravitation; Force vs. work | Force proportional to slope; Longer ramp -> greater slope | Work/energy theorem or force as a vector |
| 8b1 | Work | Different length, same height | Work |  | W=F x d; Force proportional to slope; Longer ramp -> greater slope | Work-energy |
| 9 | Work |  | Work | Gravitation; Force vs. work | W= ΔPE; ΔPE=mgh | Work/energy theorem |
| 10 | Work | Ramp; Lifting | Work | Gravitation; Force vs. work; MA | W= ΔPE; ΔPE=mgh | Work/energy theorem |
| 11 | Work | Smooth surface; Rough surface | Work & friction | Gravitation; Force vs. work; Normal force and friction | Friction force; work | Work done to overcome friction |
| 12 | Work | Same length, different height | Work & Work/Energy Theorem | Gravitation; Force vs. work | W= ΔPE; ΔPE=mgh | Work/energy theorem or force as a vector |
| 13 | Work | Three ramps: same length, different height | Work/Energy Theorem | Gravitation; Force vs. work; MA | W= ΔPE; ΔPE=mgh | Work/energy |
| 14 | MA | Different length, same height | MA | Gravitation; Force vs. work; MA | MA | Force as a vector, MA |
| 15 | MA | Different length and height (proportional) | MA | Gravitation; Force vs. work; MA | MA; slope= rise/run or proportions are equal | Force as a vector, MA |
| 16 | MA | Different length, same height | MA | Gravitation; Force vs. | MA | Force as a vector, MA |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | work; MA | | |
| 17 | PE | Same length, different height | PE | Gravitation | ΔPE=mgh | Potential |
| 18 | PE | Different length, same height | PE | Gravitation | ΔPE=mgh | Potential |
| 19 | W/PE | Smooth surface | Work/energy theorem | Gravitation | W= ΔPE if friction is negligible | Work-energy |
| 20 | W/PE | Rough surface | Work/energy theorem & friction | Force vs. work | W> ΔPE when friction isn’t negligible | Failure of work-energy when friction is substantial |

# Appendix E - Physical World Spring 2009: Pulley Worksheets

During the Physical World Spring 2009 pulley study, students completed experiments with physical and virtual pulley manipulatives. They recorded their data and answers to prompts and analysis questions on worksheets, like the one reproduced on the next pages. This worksheet was used by students in the physical-virtual sequence.

Name: ________________________________________

Group #: __________________(Will be provided to you)

# Pulley Challenge

Your group has been asked to lift a pool table into a van. When lifting the pool table, your group needs to reduce the effort force that is required. A friend suggests that a way of doing this is to use a pulley.

Using a small mass to model the pool table, your group will experiment with various pulleys to select the best method to lift the pool table into the van.

## Predictions

On your own: Answer the questions below. For each question, indicate your reasoning.

1. What factors affect the **effort force** needed to lift an object using a pulley setup? Explain your reasoning.

2. What factors affect the **work** needed to lift an object using a pulley setup? Explain your reasoning.

**In your group:** Make your prediction as a group about the best way to set up pulleys to reduce effort.

RV (Yellow) 4

## Pulley Group Questions

In a few minutes, you will research some of the science concepts related to pulleys. Below, make a list of questions you would like to research in order to design the best pulley system to move the pool table into the van. Feel free to include any "non-science" issues that may also affect your pulley choice.

# Find out More about Pulleys on CoMPASS

*Pulley Challenge:* Your group has been asked to pool table into a van using pulleys. Use the CoMPASS website* to explore the science concepts related to inclined planes. Use the space below to record the information you read about in CoMPASS.

| | |
|---|---|
| | How can you design the best possible pulley system to get the pool table into the van?<br>*Hints:*<br>Think about the science concepts that you need to explore to design the best possible pulley system.<br>Before clicking on a concept in CoMPASS, think about how information about the concept will help you in your challenge.<br>The maps in CoMPASS will show you concepts that are related to the one you are reading. Use the maps to find out more information! |

*CoMPASS website is: http://www.compassproject.net

# Pulley Hands-On Experiment

Use the available materials to set up and test some pulley systems. You may try different pulley systems out, but **be sure to record your data for each set up in the table below**.

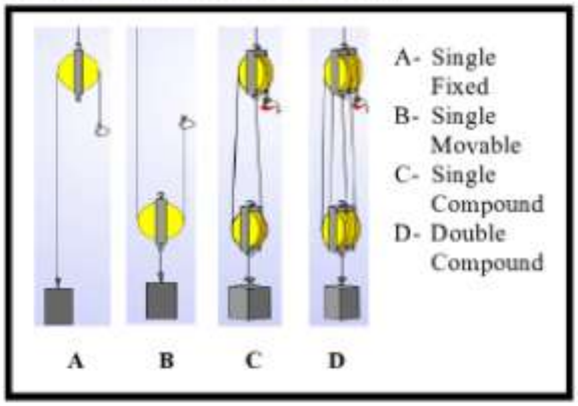
## Pulley Basics

To the right are examples of pulley setups we will investigate.

Use an object of mass 500 g in this experiment as the mock pool table in your experiment.

Pull the string at the end of the pulley not attached to the object, such that the object moves up a distance 0.10 m

Use the chart below to record your data and calculate the information needed below.



A- Single Fixed
B- Single Movable
C- Single Compound
D- Double Compound

Load (N) = <u>4.9 N</u> (due to the 500 g object that you are lifting)

| Pulley System | Direction of Force Changed? (circle one) | Effort Force (N) | Distance Pulled to Move Object (m) | Distance Object Moved* (m) | Work (J) | Potential Energy (J) | Mechanical Advantage MA | Rank Your Best Trial[$] |
|---|---|---|---|---|---|---|---|---|
| Single Fixed | Yes / No | | | 0.10m | | | | |
| Single Movable | Yes / No | | | 0.10m | | | | |
| Single Compound | Yes / No | | | 0.10m | | | | |
| Double Single Compound | Yes / No | | | 0.10m | | | | |

Reminder:

Work = Effort force x Distance Pulled

Mechanical Advantage (MA) = Load ÷ Effort Force

Potential Energy = Load x Distance Object Moved

[$] To rank 'best' trial think about which pulley system you would use to accomplish your challenge.

1. Based on your data, which pulley set-up required the **smallest effort (force)** to lift the load?

________________________________________

________________________________________

________________________________________

Why do you think that is?

________________________________________

________________________________________

________________________________________

________________________________________

2. Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?

________________________________________

________________________________________

________________________________________

Why do you think that is?

________________________________________

________________________________________

________________________________________

________________________________________

3. Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?

________________________________________

________________________________________

________________________________________

Why do you think that is?

________________________________________

________________________________________

________________________________________

________________________________________

4. Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?

Why do you think that is?

5. Based on your data, how does **work** compare to **potential energy** for a given pulley system?

Why do you think that is?

6. Which pulley setup gave you the *greatest* **mechanical advantage**?

Why do you think that is?

7. Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

Why do you think that is?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

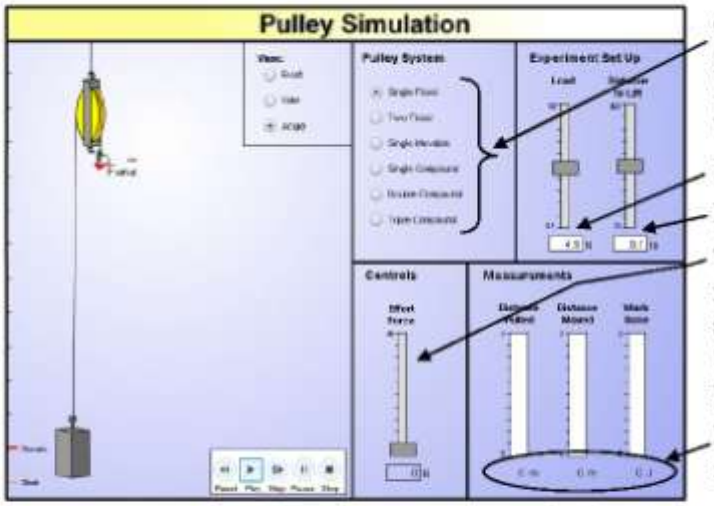
**Please tell the instructor that you have reached this point**

Name: ________________________________________

Group #: __________________(Will be provided to you)

## Pulley Virtual Experiment

You will now use the pulley simulation. Go to: http://www.compassproject.net/sims/pulley.html



Choose the pulley system as per the chart below.
Set the parameters as per the figure

Load = 4.9 N

Distance to Lift = 0.10 m

To find the effort force required to move the load, slowly increase the effort force until the load begins to move.

Record various information in the chart below.

Try each of the pulley configurations listed below

| Pulley System | Direction of Force Changed? (circle one) | Effort Force (N) | Distance Pulled to Move Object (m) | Distance Object Moved (m) | Work (J) | Potential Energy (J) | Mechanical Advantage MA | Rank Your Best Trial[$] |
|---|---|---|---|---|---|---|---|---|
| Single Fixed | Yes /No | | | 0.10 m | | | | |
| Single Movable | Yes / No | | | 0.10 m | | | | |
| Single Compound | Yes / No | | | 0.10 m | | | | |
| Double Compound | Yes / No | | | 0.10 m | | | | |

Reminder: Work = Effort force x Distance Pulled

Mechanical Advantage = Load ÷ Effort force

Potential Energy = Load x Distance Object Moved

[$] To rank 'best' trial think about which pulley system you would use to accomplish your challenge.

1. Based on your data, which pulley set-up required the **smallest effort (force)** to lift the load?

   Why do you think that is?

2. Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?

   Why do you think that is?

3. Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?

   Why do you think that is?

4. Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?

Why do you think that is?

5. Based on your data, how does **work** compare to **potential energy** for a given pulley system?

Why do you think that is?

6. Which pulley setup gave you the *greatest* **mechanical advantage**?

Why do you think that is?

7. Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?

Why do you think that is?

8. How does the relationship between **work** and **potential energy** in the *experiment* compare with the *simulation*?

Why do you think that is?

9. How does the relationship between **mechanical advantage** and the **number of supporting strands** in the *experiment* compare with the *simulation*?

Why do you think that is?

## Challenge

What would be the best way to get the pool table into the van? Explain your answer based on what you have learned from this unit.

## Feedback Questions

Please answer the following questions about the unit you just completed. Your feedback is very valuable for us!

1. Which set of activities was more helpful, the simulations or the physical, hands-on activities? Why?

2. Which set of activities did you enjoy more?

3. Did any part of the unit seem not to relate to the challenge? If so, please explain.

4. What science concepts seem to relate to the challenge?

# Appendix F - Physical World Fall 2009: Pulley Worksheets

During the Physical World Spring 2009 pulley study, students completed experiments with physical and virtual pulley manipulatives. All students used both physical and virtual manipulatives, but in different sequences. They recorded their data and answers to prompts and analysis questions on worksheets, like the one reproduced on the next pages. This worksheet was used by students in the physical-virtual sequence.

Name: ________________________________________

Group #: __________________(Will be provided to you)

## Pulley Challenge

Your group has been asked to lift a pool table into a van. When lifting the pool table, your group needs to reduce the effort force that is required. A friend suggests that a way of doing this is to use a pulley.

Your group will experiment with various model pulleys to select the best method to lift the pool table into the van.

## Pulley Group Questions

In a few minutes, you will research some of the science concepts related to pulleys. Below, make a list of questions you would like to research in order to design the best pulley system to move the pool table into the van. Feel free to include any "non-science" issues that may also affect your pulley choice.

RV (Yellow) 2

# Find out More about Pulleys on CoMPASS

| | |
|---|---|
| *Pulley Challenge:* Your group has been asked to pool table into a van using pulleys. Use the CoMPASS website* to explore the science concepts related to inclined planes. Use the space below to record the information you read about in CoMPASS. | |
| | How can you design the best possible pulley system to get the pool table into the van?<br>*Hints:*<br>Think about the science concepts that you need to explore to design the best possible pulley system.<br>Before clicking on a concept in CoMPASS, think about how information about the concept will help you in your challenge.<br>The maps in CoMPASS will show you concepts that are related to the one you are reading. Use the maps to find out more information! |

*CoMPASS website is: http://www.compassproject.net

## Pulley Hands-On Experiment

Use the available materials to set up and test some pulley systems. You may try different pulley systems out, but **be sure to record your data for each set up in the table below**.

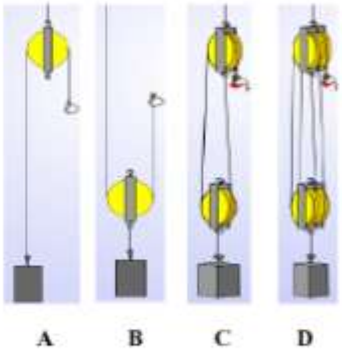
### Pulley Basics

To the right are examples of pulley setups we will investigate.

Use an object of mass 500 g in this experiment as the mock pool table in your experiment.

Pull the string at the end of the pulley not attached to the object, such that the object moves up a distance 0.10 m

Use the chart below to record your data and calculate the information needed below.



A- Single Fixed
B- Single Movable
C- Single Compound
D- Double Compound

Load (N) = 4.9 N (due to the 500 g object that you are lifting)

| Pulley System | Does the object move in the *same* direction as the applied force? | Effort Force (N) | Distance Pulled to Move Object (m) | Distance Object Moved (m) | Work (J) | Potential Energy (J) | Mechanical Advantage MA |
|---|---|---|---|---|---|---|---|
| Single Fixed | Yes /No | | | 0.10 m | | | |
| Single Movable | Yes / No | | | 0.10 m | | | |
| Single Compound | Yes / No | | | 0.10 m | | | |
| Double Compound | Yes / No | | | 0.10 m | | | |

Reminder: Work = Effort force x Distance Pulled

Mechanical Advantage (MA) = Load ÷ Effort Force

Potential Energy = Load x Distance Object Moved

Which pulley system would you choose to lift the pool table? ______________________________

______________________________________________________________

RV (Yellow) 4

1. Based on your data, which pulley set-up required the **smallest effort (force)** to lift the load?

Why do you think that is?

2. Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?

Why do you think that is?

3. Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?

Why do you think that is?

4. Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?

Why do you think that is?

5. Based on your data, how does **work** compare to **potential energy** for a given pulley system?

Why do you think that is?

6. Which pulley setup gave you the *greatest* **mechanical advantage**?

Why do you think that is?

7. Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?

Why do you think that is?

**Please tell the instructor that you have reached this point**

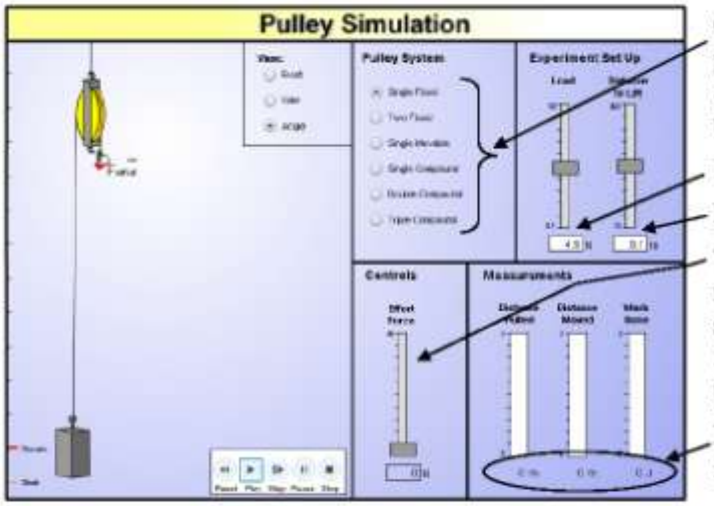
Name: ______________________________________

Group #: _________________(Will be provided to you)

RV (Blue) 1

# Pulley Virtual Experiment

You will now use the pulley simulation. Go to: http://www.compassproject.net/sims/pulley.html



Choose the pulley system as per the chart below.
Set the parameters as per the figure

Load = 0.49 N

Distance to Lift = 0.10 m

To find the effort force required to move the load, slowly increase the effort force until the load begins to move.

Record various information in the chart below.

Try each of the pulley configurations listed below

| Pulley System | Does the object move in the *same* direction as the applied force? | Effort Force (N) | Distance Pulled to Move Object (m) | Distance Object Moved (m) | Work (J) | Potential Energy (J) | Mechanical Advantage MA |
|---|---|---|---|---|---|---|---|
| Single Fixed | Yes /No | | | 0.10 m | | | |
| Single Movable | Yes / No | | | 0.10 m | | | |
| Single Compound | Yes / No | | | 0.10 m | | | |
| Double Compound | Yes / No | | | 0.10 m | | | |

Reminder: Work = Effort force x Distance Pulled

Mechanical Advantage = Load ÷ Effort force

Potential Energy = Load x Distance Object Moved

Which pulley system would you choose to lift the pool table? ______________________

______________________________________________

RV (Blue) 2

1. Based on your data, which pulley set-up required the **smallest effort (force)** to lift the load?

   Why do you think that is?

2. Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?

   Why do you think that is?

3. Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?

   Why do you think that is?

4. Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?

Why do you think that is?

5. Based on your data, how does **work** compare to **potential energy** for a given pulley system?

Why do you think that is?

6. Which pulley setup gave you the *greatest* **mechanical advantage**?

Why do you think that is?

7. Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?

Why do you think that is?

8. How does the relationship between **work** and **potential energy** in the *experiment* compare with the *simulation*?

Why do you think that is?

9. How does the relationship between **mechanical advantage** and the **number of supporting strands** in the *experiment* compare with the *simulation*?

Why do you think that is?

## Challenge

What would be the best way to get the pool table into the van? Explain your answer based on what you have learned from this unit.

## Feedback Questions

Please answer the following questions about the unit you just completed. Your feedback is very valuable for us!

1. Which set of activities was more helpful, the simulations or the physical, hands-on activities?

Why?

2. Which set of activities did you enjoy more?

Why?

3. Which set of data would you trust more, the data from the physical experiment or the data from the simulation?

Why?

# Appendix G - Physical World Fall 2009: Pulley Test

In the Physical World Fall 2009 pulley study, students answered the majority of question on Scantron sheets. The questions were provided on worksheets, like those reproduced on the following pages. One calculation question was provided on a separate sheet so that students could write their responses directly on the sheet. This question is included as the final page of Appendix G.

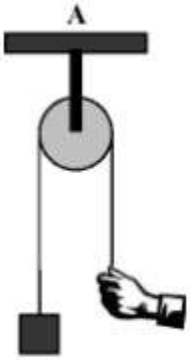
# QUESTIONS ABOUT PULLEYS

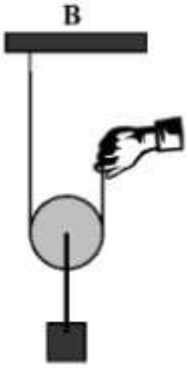
**PLEASE DO NOT WRITE ANYTHING ON THESE SHEETS.**

**PLEASE USE SCANTRON SHEETS PROVIDED TO ANSWER THE QUESTIONS BELOW.**

**BE SURE TO FILL IN YOUR WID NUMBER ON THE SCANTRON**

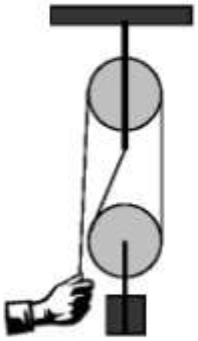
**Q1**) If we ignore friction, which of the following two pulleys setups will require *less effort* (force) to lift the load?





A.) Pulley A
B.) Pulley B
C.) Both Pulley A & Pulley B will require the same effort (force)
D.) Not enough information to decide

**Q2**) If we ignore friction, which will require *less effort* (force) to lift a box to a height of 1 meter – using the pulley shown or lifting the box straight up?



A.) Using the pulley
B.) Lifting it straight up
C.) Both using the pulley or lifting it straight up require the same effort (force)
D.) Not enough information to decide

**Q3**) You use a fixed pulley to lift a watermelon to your tree house. If you changed it to a movable pulley and ignore the effects of friction, the *distance* pulled would

A.) Increase
B.) Decrease
C.) Stay the same
D.) Not enough information to decide

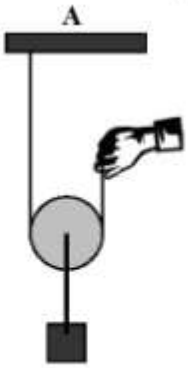
**Q4**) You use a fixed pulley to lift a watermelon to your tree house. If you changed it to a movable pulley and ignore the effects of friction, the *effort* (force) required would:

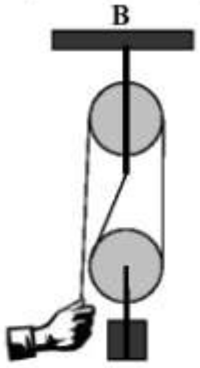
A.) Increase
B.) Decrease
C.) Stay the same
D.) Not enough information to decide

**Q5**) Which of the following will require *less effort* (force) to lift a load to a height of 2 m using a single fixed pulley?

A.) A well-oiled pulley
B.) A pulley that sticks (needs to be oiled)
C.) Both pulleys will require the same effort (force)
D.) Not enough information to decide

**Q6**) If we ignore friction, which of the following pulley setups will require *less effort* (force) to lift the load?





A.) Pulley Setup A
B.) Pulley Setup B
C.) Both A and B will require the same effort (force)
D.) Not enough information to decide

**Q7**) If we ignore friction, which one of the following pulley set-ups will require *less effort* (force) to lift a load?

A.) One fixed pulley
B.) Two fixed pulleys
C.) One movable pulley
D.) A double compound pulley

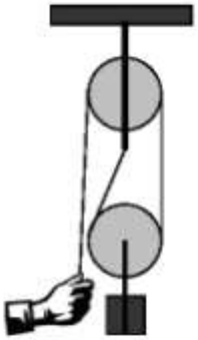
**Q8)** You used a single fixed pulley to lift a watermelon to your tree house. If you used a single movable pulley instead and ignore the effects of friction, the *effort* (force) needed would

- A.) Increase
- B.) Decrease
- C.) stay the same
- D.) not enough information to decide

**Q9)** You used a single fixed pulley to lift a watermelon to your tree house. If you used a single movable pulley instead and ignore the effects of friction, the *work* done would:

- E.) Increase
- F.) Decrease
- G.) stay the same
- H.) not enough information to decide

**Q10)** Jane is lifting a box straight up to a height of 1 m. Mary is using the pulley shown below to lift the same box to the same height. If we ignore friction, what can you tell about the *work* done by Jane and Mary?

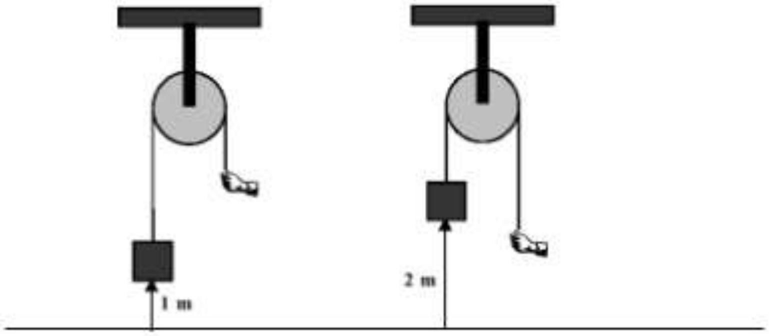


- A.) Jane is doing more work
- B.) Mary is doing more work
- C.) Jane and Mary are doing the same work
- D.) Not enough information to decide

**Q11)** Which of the following will require more *work* to lift a load to a height of 2 m if you are using a single fixed pulley?

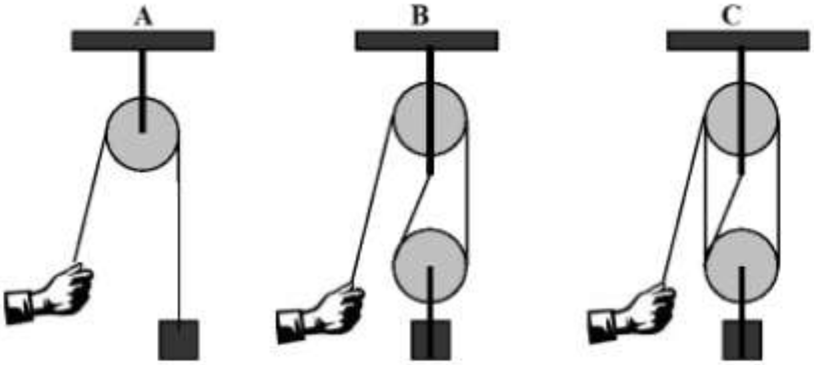
- A.) A well-oiled pulley
- B.) A pulley that sticks (needs to be oiled)
- C.) Both pulleys will require the same work
- D.) Not enough information to decide

**Q12**) Jacob is using a fixed pulley to separately lift two boxes of the same size and mass up to two different heights. He lifts one box 1 meter and then lifts the second box 2 meters above the ground. Ignoring friction, when lifting the box 2 meters, Jacob is doing _____________ *work* as/than when lifting the first box 1 meter high?



A.) More
B.) Less
C.) Same amount of
D.) Not enough information to decide

**Q13**) Amy is using pulley set-up A, Bob is using B, and Cathy is using C. What can you tell about the *work* needed to lift the same load to the same height by each of them, if we ignore friction?



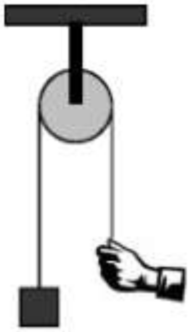
A.) Amy (using pulley system A) is doing more work
B.) Bob (using pulley system B) is doing more work
C.) Cathy (using pulley system C) is doing more work
D.) The work done in all three situations is the same

**Q14)** If we ignore friction, which one of the following pulley set-ups will give more *mechanical advantage*?

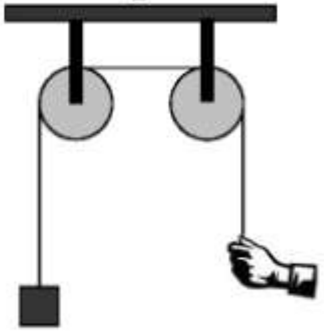
A.) One fixed pulley
B.) Two fixed pulleys
C.) One movable pulley
D.) A double compound pulley

**Q15)** If we ignore friction, which one of the following pulley set ups will give more *mechanical advantage*?

**A**



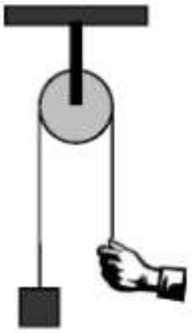
**B**



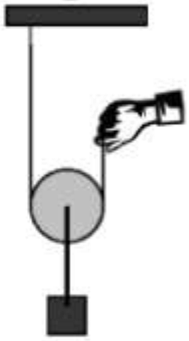
A.) Pulley set up A
B.) Pulley set up B
C.) Pulley set up A and Pulley set up B will give you the same mechanical advantage
D.) Not enough information

**Q16)** If we ignore friction, which one of the following pulley set ups will give more *mechanical advantage*?

**A**

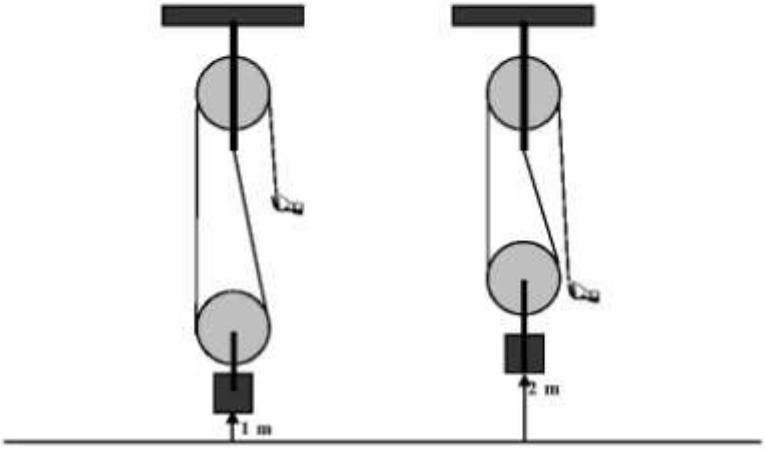


**B**



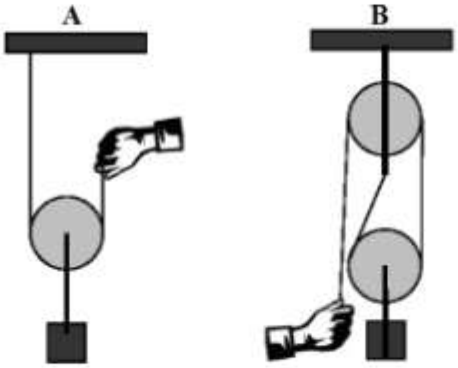
A.) Pulley set up A
B.) Pulley set up B
C.) Pulley set up A and Pulley set up B will give you the same mechanical advantage
D.) Not enough information

**Q17**) Yi uses a single compound pulley to lift a box 1 m. He then uses the same pulley to lift an identical box 2 m. Which box undergoes a greater change in *potential energy*?



A.) The box lifted 1 m
B.) The box lifted 2 m
C.) Both boxes have the same change in potential energy
D.) Not enough information to decide

**Q18**) Louis lifts a box 1 m using Pulley Setup A. Toby lifts an identical box to the same height using Pulley Setup B. Which box undergoes a *greater change in potential energy*?



A.) The box on Pulley Setup A
B.) The box on Pulley Setup B
C.) Both boxes have the same change in potential energy
D.) Not enough information to decide

**Q19**) Henry uses a well-oiled double compound pulley to lift a box 1 m. If you can ignore friction, how does the work to lift the box compare to the box's change in potential energy while being lifted?

A.) The work needed is greater than the change in potential energy
B.) The work needed is less than the change in potential energy
C.) The work needed is the same as the change in potential energy
D.) Not enough information to decide

**Q20**) Gloria uses a squeaky (needs to be oiled) double compound pulley to lift a box 1 m. If you **cannot** ignore friction, how does the work to lift the box compare to the box's change in potential energy while being lifted?

A.) The work needed is greater than the change in potential energy
B.) The work needed is less than the change in potential energy
C.) The work needed is the same as the change in potential energy
D.) Not enough information to decide

**Q21) THIS IS NOT A MULTIPLE CHOICE QUESTION. PLEASE ANSWER THIS QUESTION ON THE SEPARATE SHEET THAT IS PROVIDED.**

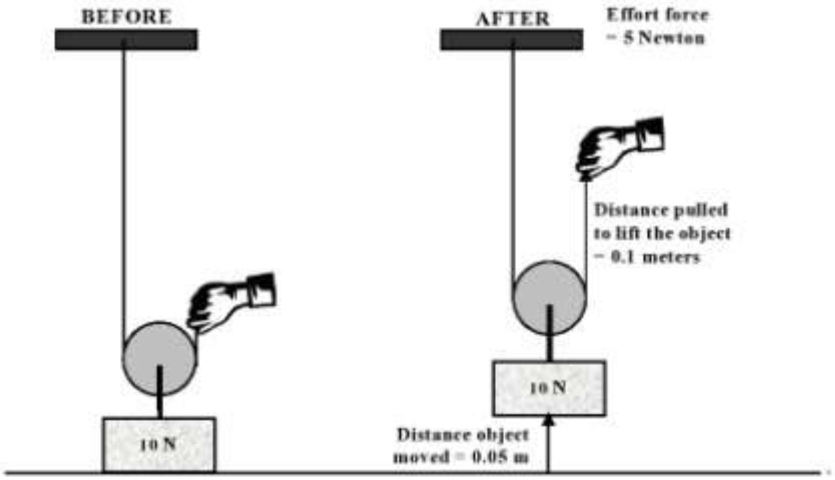
## QUESTIONS ABOUT PULLEYS

**NAME (PLEASE PRINT):** ____________________________________________________________

**Q1) THOUGH Q20):**

**THESE WILL BE PROVIDED ON A SEPARATE SHEET. PLEASE ANSWER THESE MULTIPLE CHOICE QUESTIONS ON THE SCANTRON SHEET PROVIDED.**

**Q21**) Below are before and after pictures of a load being lifted with the help of a pulley. Ignoring friction, find calculate the *work* done using the information from the picture below:



Do your calculations below. Clearly show any formulas and values that you use.

# Appendix H - Concepts of Physics Fall 2009: Wrap Up Questions

In the Concepts of Physics Fall 2009 pulley study, the students responded to Wrap Up Questions in the Activity Center after completing both the physical and virtual activities. These questions were designed to explore the students' understanding of the similarities and differences between the physical and virtual experiments.

**Name:** ____________________________________________

## Wrap-up Questions

1. In what ways was the computer simulation pulley experiment *similar* to the physical pulley experiment?

2. In what ways was the computer simulation pulley experiment *different* from the physical pulley experiment?

3. What may have caused differences between the data you got from the physical pulley experiment and the data you got from the computer simulation experiment?

4. If there were differences between the data from your physical pulley experiment and your computer simulation experiment, which would you trust more?

Why?

# Appendix I - Concepts of Physics Fall 2009: Survey

In the Concepts of Physics Fall 2009 pulley study, the students responded to a survey designed to explore their ideas about the usefulness of data from physical and virtual experiments.  The survey is reproduced on the following pages.

## SURVEY

**NAME (PLEASE PRINT ALL CAPS)**____________________________________

**THERE ARE NO RIGHT OR WRONG ANSWERS TO QUESTIONS BELOW**

**Select the answer that MAKES MOST SENSE to YOU.**
**Clearly explain what led you to make that choice.**

### Question 1

On a test your professor has asked you some questions about several pulley setups.

**A)** On the first question on the test, you have to decide whether a **fixed** or **movable** pulley requires the ***least effort force*** to lift the load.

Which experience in the Activity Center would better help you answer this question? (Check **one**)

☐ Experiment with real pulleys ☐ Computer simulation of pulleys ☐ Both are equally helpful

- ➢ Explain what led you to make the choice above

**B)** On the second question on the test, you have to decide if a **fixed** or **movable** pulley requires the ***least work*** to lift the load.

Which experience in the Activity Center would better help you answer this question? (Check **one**)

☐ Experiment with real pulleys ☐ Computer simulation of pulleys ☐ Both are equally helpful

- ➢ Explain what led you to make the choice above

**C)** On the third question on the test, you have to decide if a **movable** pulley or a **double compound** pulley requires the ***least effort force*** to lift the load.

Which experience in the Activity Center would better help you answer this question? (Check **one**)

☐ Experiment with real pulleys ☐ Computer simulation of pulleys ☐ Both are equally helpful

- ➢ Explain what led you to make the choice above

**D)** On the fourth question on the test, you have to decide if a **movable** pulley or a **double compound** pulley requires the ***least work*** to lift the load.

Which experience in the Activity Center would better help you answer this question? (Check **one**)

☐ Experiment with real pulleys ☐ Computer simulation of pulleys ☐ Both are equally helpful

- ➢ Explain what led you to make the choice above

## Question 2

You need to rent a pulley system to help lift an oversized dresser to the second floor balcony of your home. An employee at your local rental store informs you they have several pulleys you can rent.

To help you decide which pulleys to rent, she offers to let you try out either with *real toy pulleys* or a *computer simulation of pulleys*

**A)** At the rental store, you have to choose between a **fixed pulley** and a **movable pulley** to help you lift the bed. What would you try out with to help you make your decision? (Check **one**)

☐ Real toy pulleys ☐ Computer simulation of pulleys ☐ Both are equally helpful

➢ Explain what led you to make the choice above

**B)** At the rental store, you have to choose between a **movable pulley** and a **double compound pulley** to help you lift the bed. What would you try out with to help you make your decision? (Check **one**)

☐ Real toy pulleys ☐ Computer simulation of pulleys ☐ Both are equally helpful

➢ Explain what led you to make the choice above

## Question 3

Imagine you had been sick this week and were unable to go to the Activity Center for the Pulley Activities. Other students in the class had completed experiments with real pulleys as well as a computer simulation of pulleys.

To help you answer your homework questions, your kind professor sends you **his own data** from the real pulley experiments as well as **his own data** from the computer simulation of pulleys.

**A)** In the first homework question, you are asked to decide what kind of pulley system would require the ***least effort force*** to lift the load. Which of the professor's data would you prefer to use? (Check **one**)

☐ Data from real pulleys ☐ Data from computer simulation of pulleys ☐ Both equally preferred

➢ Explain what led you to make the choice above

**B)** In the second homework question, you are asked to decide what kind of pulley system would require the ***least work*** to lift the load. Which of the professor's data would you prefer to use? (Check **one**)

☐ Data from real pulleys ☐ Data from computer simulation of pulleys ☐ Both equally preferred

➢ Explain what led you to make the choice above

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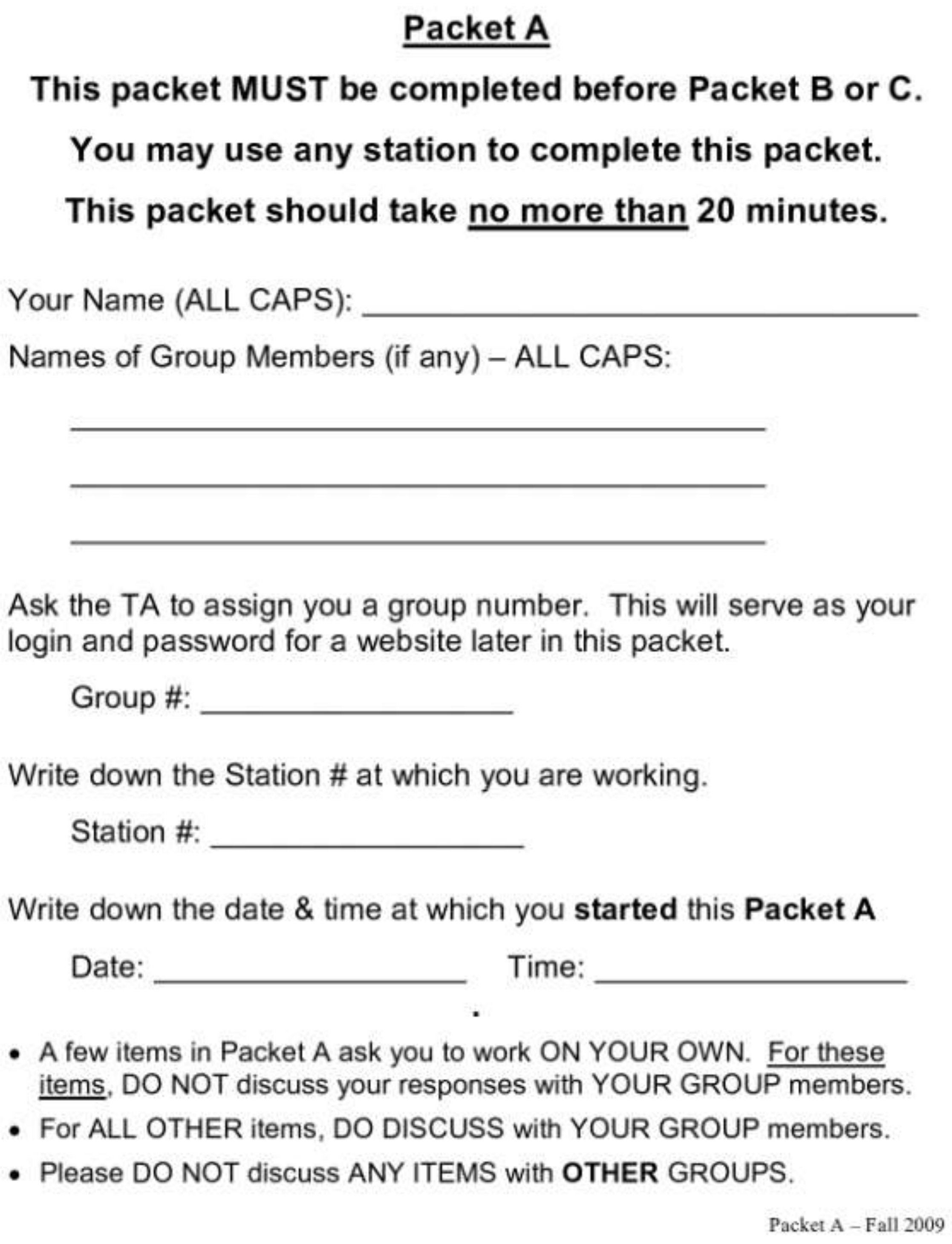
# Appendix J - Concepts of Physics Fall 2009: Pulley Worksheet

In the Concepts of Physics Fall 2009 pulley study, students chose the order in which they completed the physical and virtual experiments. In order to facilitate this process, the worksheets were provided to students as three separate packets, reproduced on the following pages. Packet A contained the pre-experiment details, such as making predictions and using the CoMPASS hypertext system. Packet B contained the physical experiment, and Packet C contained the virtual experiment. Students could complete Packet B and Packet C in the order of their choosing.



## Packet A

**This packet MUST be completed before Packet B or C.**

**You may use any station to complete this packet.**

**This packet should take no more than 20 minutes.**

Your Name (ALL CAPS): ____________________

Names of Group Members (if any) – ALL CAPS:

____________________

____________________

____________________

Ask the TA to assign you a group number. This will serve as your login and password for a website later in this packet.

Group #: ____________

Write down the Station # at which you are working.

Station #: ____________

Write down the date & time at which you **started** this **Packet A**

Date: ____________ Time: ____________

- A few items in Packet A ask you to work ON YOUR OWN. For these items, DO NOT discuss your responses with YOUR GROUP members.
- For ALL OTHER items, DO DISCUSS with YOUR GROUP members.
- Please DO NOT discuss ANY ITEMS with **OTHER** GROUPS.

Packet A – Fall 2009

## Pulley Challenge

Your group has been asked to lift a pool table into a van. When lifting the pool table, your group needs to reduce the effort force that is required. A friend suggests that a way of doing this is to use a pulley.

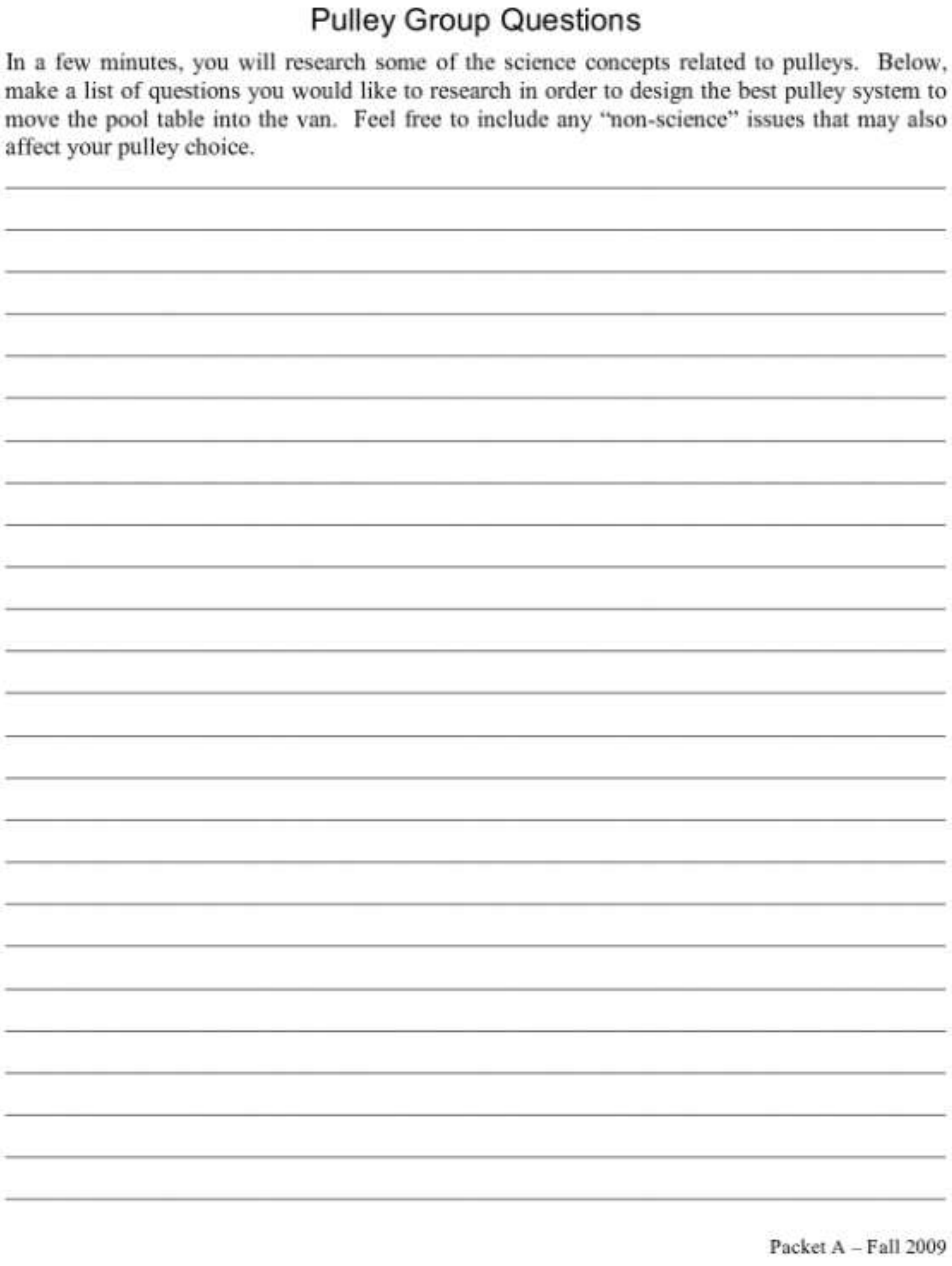
## Predictions

On your own: Answer the questions below. For each question, indicate your reasoning.

1. What factors affect the **effort force** needed to lift an object using a pulley setup? Explain your reasoning.

2. What factors affect the **work** needed to lift an object using a pulley setup? Explain your reasoning.

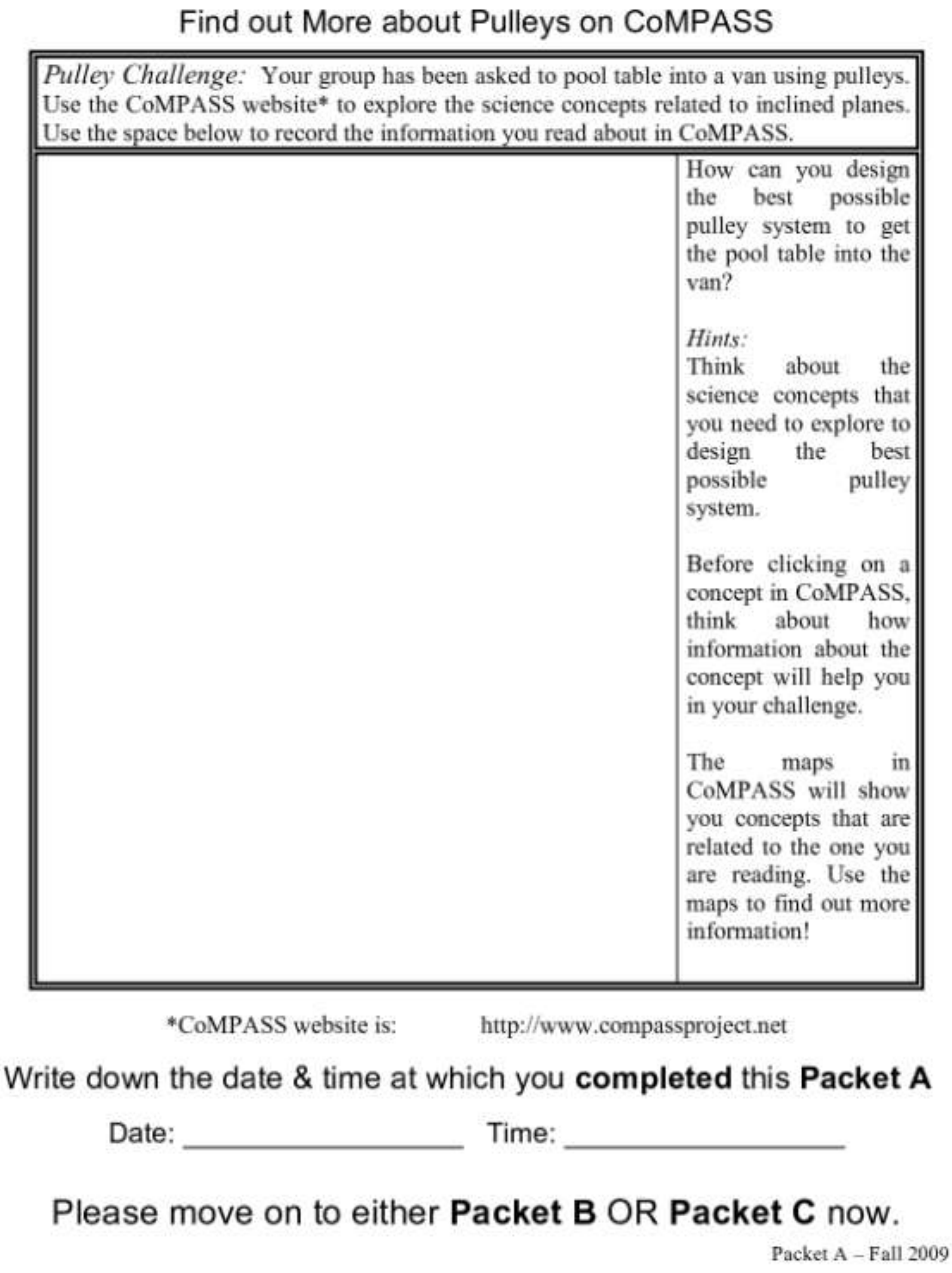
In your group: Make your prediction as a group about the best way to set up pulleys to reduce effort.



## Pulley Group Questions

In a few minutes, you will research some of the science concepts related to pulleys. Below, make a list of questions you would like to research in order to design the best pulley system to move the pool table into the van. Feel free to include any "non-science" issues that may also affect your pulley choice.

Packet A – Fall 2009



## Find out More about Pulleys on CoMPASS

| | |
|---|---|
| *Pulley Challenge:* Your group has been asked to pool table into a van using pulleys. Use the CoMPASS website* to explore the science concepts related to inclined planes. Use the space below to record the information you read about in CoMPASS. | |
| | How can you design the best possible pulley system to get the pool table into the van?<br>*Hints:*<br>Think about the science concepts that you need to explore to design the best possible pulley system.<br>Before clicking on a concept in CoMPASS, think about how information about the concept will help you in your challenge.<br>The maps in CoMPASS will show you concepts that are related to the one you are reading. Use the maps to find out more information! |

*CoMPASS website is: http://www.compassproject.net

Write down the date & time at which you **completed** this **Packet A**

Date: ____________________ Time: ____________________

Please move on to either **Packet B** OR **Packet C** now.

Packet A – Fall 2009

# Packet B

**You MUST have completed Packet A before this Packet.**

**You may use any of these stations to complete Packet B: Stations 1, 2, 3 or 4.**

**This packet should take no more than 35 minutes.**

Your Name (ALL CAPS): ______________________________

Names of Group Members (if any) – ALL CAPS:

______________________________________

______________________________________

______________________________________

Group #: _________________
(Use the SAME number the TA gave you for **Packet A**)

Write down the Station # at which you are working on.

Station #: _________________

Write down the date & time at which you **started** this **Packet B**

Date: _________________ Time: _________________

Are you doing this packet BEFORE **Packet C**?

Yes No (Circle one)

## Pulley Hands-On Experiment

Use the available materials to set up and test some pulley systems. You may try different pulley systems out, but **be sure to record your data for each setup in the table below**.

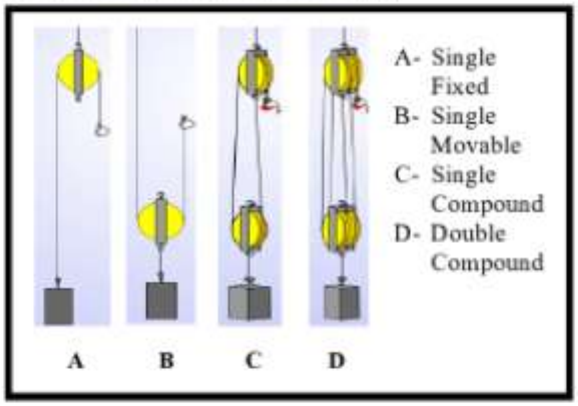
### Pulley Basics

To the right are examples of pulley setups we will investigate.

Use an object of mass 500 g in this experiment as the mock pool table in your experiment.

Pull the string at the end of the pulley not attached to the object, such that the object moves up a distance 0.10 m

Use the chart below to record your data and calculate the information needed below.



Load (N) = 4.9 N (due to the 500 g object that you are lifting)

| Pulley System | Direction of Force Changed? (circle one) | Effort Force (N) | Distance Pulled to Move Object (m) | Distance Object Moved* (m) | Work (J) | Potential Energy (J) | Mechanical Advantage MA | Rank Your Best Trial[$] |
|---|---|---|---|---|---|---|---|---|
| Single Fixed | Yes / No | | | 0.10m | | | | |
| Single Movable | Yes / No | | | 0.10m | | | | |
| Single Compound | Yes / No | | | 0.10m | | | | |
| Double Compound | Yes / No | | | 0.10m | | | | |

Reminder:
Work = Effort force x Distance Pulled
Mechanical Advantage (MA) = Load ÷ Effort Force
Potential Energy = Load x Distance Object Moved

---

[$] To rank 'best' trial think about which pulley system you would use to accomplish your challenge.

1. Based on your data, which pulley set-up required the **smallest effort (force)** to lift the load?

_______________________________________________

_______________________________________________

_______________________________________________

Why do you think that is?

_______________________________________________

_______________________________________________

_______________________________________________

_______________________________________________

2. Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?

_______________________________________________

_______________________________________________

_______________________________________________

Why do you think that is?

_______________________________________________

_______________________________________________

_______________________________________________

_______________________________________________

3. Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?

_______________________________________________

_______________________________________________

_______________________________________________

Why do you think that is?

_______________________________________________

_______________________________________________

_______________________________________________

_______________________________________________

4. Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?

Why do you think that is?

5. Based on your data, how does **work** compare to **potential energy** for a given pulley system?

Why do you think that is?

6. Which pulley setup gave you the *greatest* **mechanical advantage**?

Why do you think that is?

7. Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?

Why do you think that is?

Write down the date & time at which you **completed** this **Packet B**

Date: ____________________ Time: ____________________

**Please hand this Packet B back to the TA, and tell the TA that you have reached this point.**

**The TA will hand you the next instruction.**

# Packet C

## You MUST have completed Packet A before this Packet.

## You may use any of these stations to complete Packet C: Stations 5, 6, 7 or 8.

## This packet should take no more than 30 minutes.

Your Name (ALL CAPS): ______________________________

Names of Group Members (if any) – ALL CAPS:

______________________________________

______________________________________

______________________________________

Group #: _________________

(Use the SAME number the TA gave you for **Packet A**)

Write down the Station # at which you are working on.

Station #: _________________

Write down the date & time at which you **started** this **Packet C**

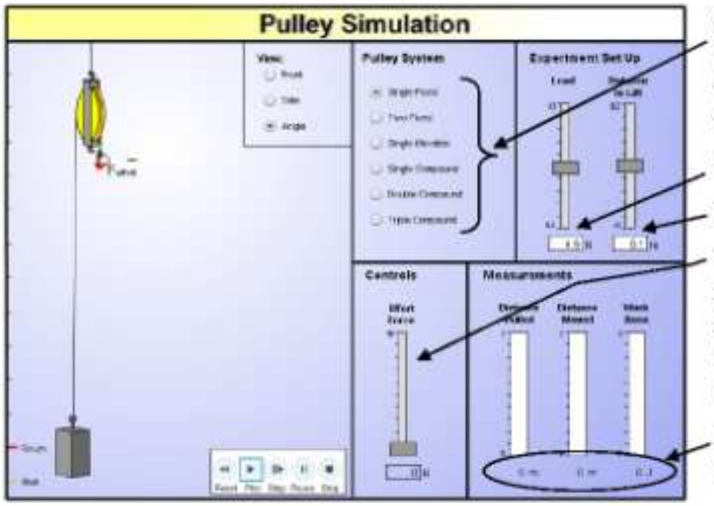
Date: _________________ Time: _________________

Are you doing this packet BEFORE **Packet B**?

Yes No (Circle one)

# Pulley Virtual Experiment

You will now use the pulley simulation.
Click on the "PULLEY SIMULATION" icon on the desktop



Choose the pulley system as per the chart below.
Set the parameters as per the figure

Load = 4.9 N

Distance to Lift = 0.10 m

To find the effort force required to move the load, slowly increase the effort force until the load begins to move.

Record various information in the chart below.

Try each of the pulley configurations listed below

| Pulley System | Direction of Force Changed? (circle one) | Effort Force (N) | Distance Pulled to Move Object (m) | Distance Object Moved (m) | Work (J) | Potential Energy (J) | Mechanical Advantage MA | Rank Your Best Trial[$] |
|---|---|---|---|---|---|---|---|---|
| Single Fixed | Yes /No | | | 0.10 m | | | | |
| Single Movable | Yes / No | | | 0.10 m | | | | |
| Single Compound | Yes / No | | | 0.10 m | | | | |
| Double Compound | Yes / No | | | 0.10 m | | | | |

Reminder:
Work = Effort force x Distance Pulled
Mechanical Advantage = Load ÷ Effort force
Potential Energy = Load x Distance Object Moved

[$] To rank 'best' trial think about which pulley system you would use to accomplish your challenge.

1. Based on your data, which pulley set-up required the **smallest effort (force)** to lift the load?

Why do you think that is?

2. Based on your data, when you *increase* the **distance you pull** to lift the object to a certain height, how does it affect the **effort force** required?

Why do you think that is?

3. Based on your data, how does the **distance you pull** compare to the **distance the object moved** for the pulley with the *smallest effort force*?

Why do you think that is?

4. Based on your data, when you **changed the pulley setup**, how did it affect the **work** required to lift the object?

Why do you think that is?

5. Based on your data, how does **work** compare to **potential energy** for a given pulley system?

Why do you think that is?

6. Which pulley setup gave you the *greatest* **mechanical advantage**?

Why do you think that is?

7. Based on your data, when you *increase* the **number of supporting strands**, how does it affect the **mechanical advantage**?

Why do you think that is?

Write down the date & time at which you **completed** this **Packet C**

Date: ____________________ Time: ____________________

**Please hand this Packet C back to the TA, and tell the TA that you have reached this point.**

**The TA will hand you the next instruction.**

# Appendix K - Concepts of Physics Fall 2009: Pulley Test

The test used in the Physical World Fall 2009 inclined plane study is included on the following pages.  Students took the test before receiving any instruction on inclined planes (as a pre-test), in between the physical and virtual experiments (as a mid-test), and after completing both experiments (as a post-test).

Name: ______________________________ Date: ______________

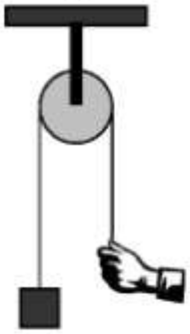
## Some Questions About Pulleys

**Please make your best effort to answer these questions. Do not be concerned if you do not know the answers to the questions. You will learn this in the Activity Center this week**

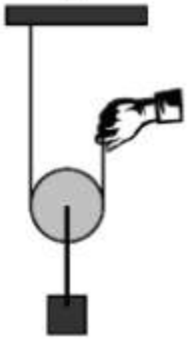
Instructions: Circle only *one* letter to indicate your answer for each question.

1) If we ignore friction, which of the following two pulleys setups will require *less effort* (force) to lift the load?

**A**

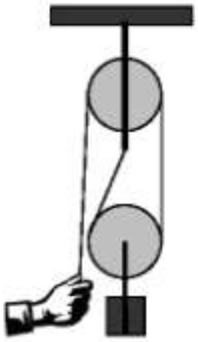


**B**



A.) Pulley A
B.) Pulley B
C.) Both Pulley A & Pulley B will require the same effort (force)
D.) Not enough information to decide

2) If we ignore friction, which will require *less effort* (force) to lift a box to a height of 1 meter – using the pulley shown or lifting the box straight up?



A.) Using the pulley
B.) Lifting it straight up
C.) Both using the pulley or lifting it straight up require the same effort (force)
D.) Not enough information to decide

3) You use a fixed pulley to lift a watermelon to your tree house. If you changed it to a movable pulley and ignore the effects of friction:

3a) the *distance* pulled would:

A.) Increase
B.) Decrease
C.) Stay the same
D.) Not enough information to decide

3b) Explain your reasoning about the *distance* pulled.

3c) the *effort* (force) required would:

A.) Increase
B.) Decrease
C.) Stay the same
D.) Not enough information to decide

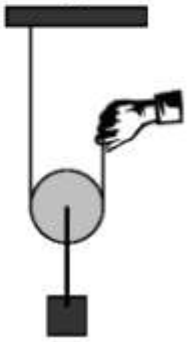
3d) Explain your reasoning about the *effort* (force) required.

5) Which of the following will require *less effort* (force) to lift a load to a height of 2 m using a single fixed pulley?

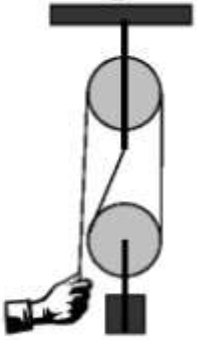
A.) A well-oiled pulley
B.) A pulley that sticks (needs to be oiled)
C.) Both pulleys will require the same effort (force)
D.) Not enough information to decide

6) If we ignore friction, which of the following pulley setups will require *less effort* (force) to lift the load?

**A**



**B**



A.) Pulley Setup A
B.) Pulley Setup B
C.) Both A and B will require the same effort (force)
D.) Not enough information to decide

7) If we ignore friction, which one of the following pulley set-ups will require *less effort* (force) to lift a load?
   A.) One fixed pulley
   B.) Two fixed pulleys
   C.) One movable pulley
   D.) A double compound pulley

8) You used a single fixed pulley to lift a watermelon to your tree house. If you used a single movable pulley instead and ignore the effects of friction:

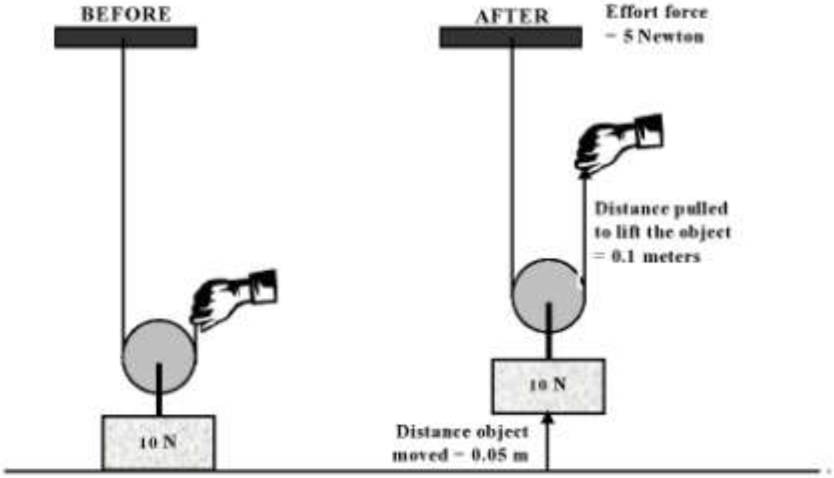
   8a-1) the *effort* (force) needed would:
      A.) Increase
      B.) Decrease
      C.) stay the same
      D.) not enough information to decide

   8a-2) Explain your reasoning about the *effort* (force) needed.

   8b-1) the *work* done would:
      E.) Increase
      F.) Decrease
      G.) stay the same
      H.) not enough information to decide

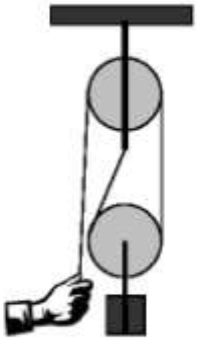
   8b-2) Explain your reasoning about the *work* done.

9) Below are before and after pictures of a load being lifted with the help of a pulley. Ignoring friction, find calculate the *work* done using the information from the picture below:



Clearly show how you arrive at your answer

10) Jane is lifting a box straight up to a height of 1 m. Mary is using the pulley shown below to lift the same box to the same height. If we ignore friction, what can you tell about the *work* done by Jane and Mary?



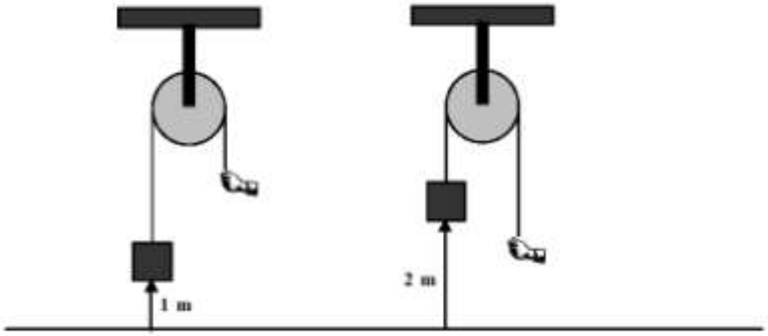
A.) Jane is doing more work
B.) Mary is doing more work
C.) Jane and Mary are doing the same work
D.) Not enough information to decide

10a) Explain your reasoning about *work* done in this question.

11) Which of the following will require more *work* to lift a load to a height of 2 m if you are using a single fixed pulley?

A.) A well-oiled pulley
B.) A pulley that sticks (needs to be oiled)
C.) Both pulleys will require the same work
D.) Not enough information to decide

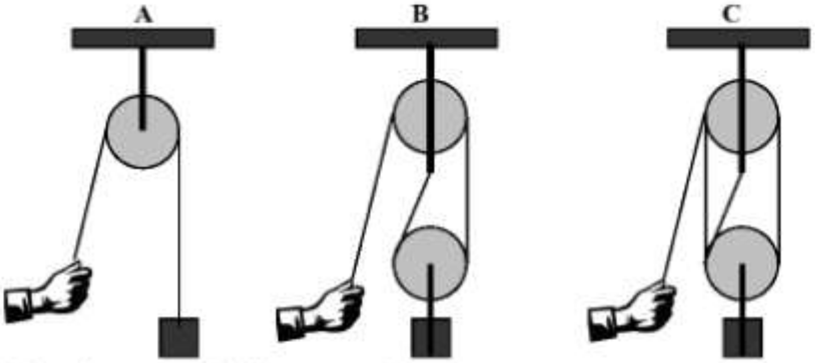
12) Jacob is using a fixed pulley to separately lift two boxes of the same size and mass up to two different heights. He lifts one box 1 meter and then lifts the second box 2 meters above the ground. Ignoring friction, when lifting the box 2 meters, Jacob is doing _____________ *work* as/than when lifting the first box 1 meter high?



A.) More
B.) Less
C.) Same amount of
D.) Not enough information to decide

12a) Explain your reasoning about *work* done in this question.

13) Amy is using pulley set-up A, Bob is using B, and Cathy is using C. What can you tell about the *work* needed to lift the same load to the same height by each of them, if we ignore friction?

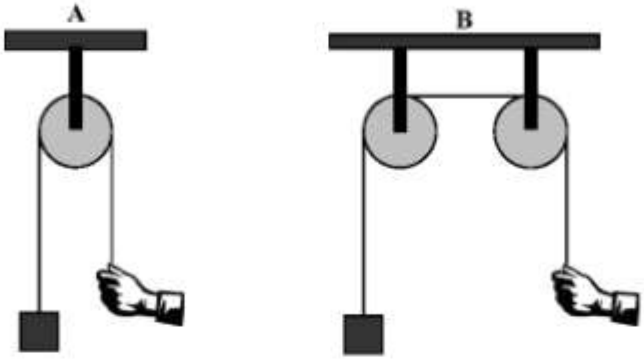


A.) Amy (using pulley system A) is doing more work
B.) Bob (using pulley system B) is doing more work
C.) Cathy (using pulley system C) is doing more work
D.) The work done in all three situations is the same

14) If we ignore friction, which one of the following pulley set-ups will give more *mechanical advantage*?
A.) One fixed pulley
B.) Two fixed pulleys
C.) One movable pulley
D.) A double compound pulley

14a) Explain your reasoning about *mechanical advantage* in this question.

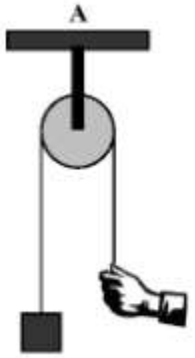
15) If we ignore friction, which one of the following pulley set ups will give more *mechanical advantage*?

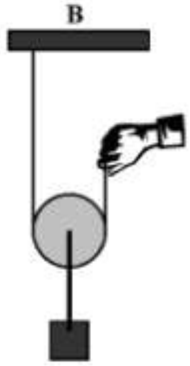


A.) Pulley set up A
B.) Pulley set up B
C.) Pulley set up A and Pulley set up B will give you the same mechanical advantage
D.) Not enough information

15a) Explain your reasoning about *mechanical advantage* in this question.

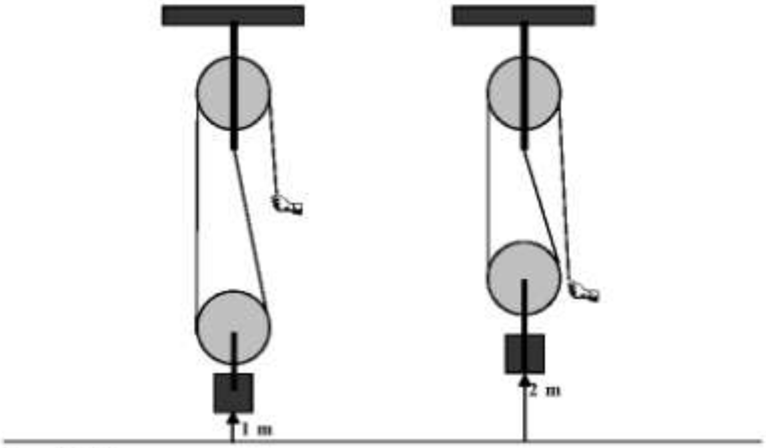
16) If we ignore friction, which one of the following pulley set ups will give more *mechanical advantage*?





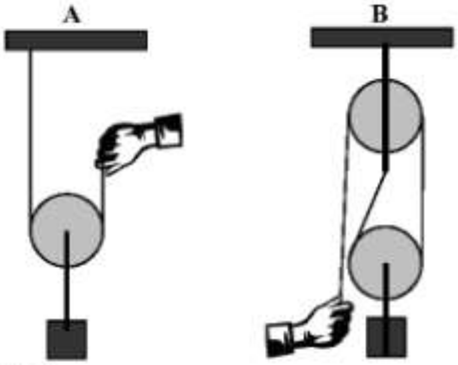
A.) Pulley set up A
B.) Pulley set up B
C.) Pulley set up A and Pulley set up B will give you the same mechanical advantage
D.) Not enough information

17) Yi uses a single compound pulley to lift a box 1 m. He then uses the same pulley to lift an identical box 2 m. Which box undergoes a greater change in *potential energy*?



A.) The box lifted 1 m
B.) The box lifted 2 m
C.) Both boxes have the same change in potential energy
D.) Not enough information to decide

18) Louis lifts a box 1 m using Pulley Setup A. Toby lifts an identical box to the same height using Pulley Setup B. Which box undergoes a *greater change in potential energy*?



A.) The box on Pulley Setup A
B.) The box on Pulley Setup B
C.) Both boxes have the same change in potential energy
D.) Not enough information to decide

19) Henry uses a well-oiled double compound pulley to lift a box 1 m. If you can ignore friction, how does the work to lift the box compare to the box's change in potential energy while being lifted?
A.) The work needed is greater than the change in potential energy
B.) The work needed is less than the change in potential energy
C.) The work needed is the same as the change in potential energy
D.) Not enough information to decide

20) Gloria uses a squeaky (needs to be oiled) double compound pulley to lift a box 1 m. If you **cannot** ignore friction, how does the work to lift the box compare to the box's change in potential energy while being lifted?
A.) The work needed is greater than the change in potential energy
B.) The work needed is less than the change in potential energy
C.) The work needed is the same as the change in potential energy
D.) Not enough information to decide

# Appendix L - Physical World Spring 2010: Survey

In the Physical World Spring 2010 pulley study, students responded to a similar survey as that used in the Concepts of Physics Fall 2009 pulley study. This survey was designed to explore students' views of the usefulness of information gathered from physical and virtual manipulatives. The main difference between the two versions of the survey was in the wording of the option that indicated that the physical and virtual manipulatives were equally useful, as discussed in the text.

# SURVEY

**NAME (PLEASE PRINT ALL CAPS)**______________________________________

**THERE ARE NO RIGHT OR WRONG ANSWERS TO QUESTIONS BELOW**

**Select the answer that MAKES MOST SENSE to <u>YOU</u>.**
**Clearly explain what led you to make that choice.**

## Question 1

You need to rent a pulley system to help lift an oversized dresser to the second floor balcony of your home. An employee at your local rental store informs you they have several pulleys you can rent.

To help you decide which pulleys to rent, she offers to let you try out either ***real toy pulleys*** OR a ***computer simulation of pulleys***

**A)** At the rental store, you have to choose between a **fixed pulley** and a **movable pulley** to help you lift the bed. What would you try out to help you make your decision? (Check **one**)

☐ Real toy pulleys ☐ Computer simulation of pulleys ☐ Either would be equally helpful

➢ Explain what led you to make the choice above.

**B)** At the rental store, you have to choose between a **movable pulley** and a **double compound pulley** to help you lift the bed. What would you try out to help you make your decision? (Check **one**)

☐ Real toy pulleys ☐ Computer simulation of pulleys ☐ Either would be equally helpful

➢ Explain what led you to make the choice above.

## Question 2

On a test your professor has asked you some questions about several pulley setups.

**A)** On the first question on the test, you have to decide whether a **fixed** or **movable** pulley requires the ***<u>least effort force</u>*** to lift the load.

Which experience from the pulley labs would better help you answer this question? (Check **one**)

☐ Real pulley experiment ☐ Computer simulation of pulleys ☐ Either would be equally helpful

➢ Explain what led you to make the choice above.

**B)** On the second question on the test, you have to decide if a **fixed** or **movable** pulley requires the ***<u>least work</u>*** to lift the load.

Which experience from the pulley labs would better help you answer this question? (Check **one**)

☐ Real pulley experiment ☐ Computer simulation of pulleys ☐ Either would be equally helpful

➢ Explain what led you to make the choice above.

**C)** On the third question on the test, you have to decide if a **movable** pulley or a **double compound** pulley requires the ***least effort force*** to lift the load.

Which experience from the pulley labs would better help you answer this question? (Check **one**)

☐ Real pulley experiment ☐ Computer simulation of pulleys ☐ Either would be equally helpful

- Explain what led you to make the choice above.

**D)** On the fourth question on the test, you have to decide if a **movable** pulley or a **double compound** pulley requires the ***least work*** to lift the load.

Which experience from the pulley labs would better help you answer this question? (Check **one**)

☐ Real pulley experiment ☐ Computer simulation of pulleys ☐ Either would be equally helpful

- Explain what led you to make the choice above.

## Question 3

Imagine you had been sick these two weeks and were unable to come to lab for the Pulley Activities. Other students in the class had completed experiments with real pulleys as well as a computer simulation of pulleys.

To help you with a make up assignment, your kind professor sends you **his own data** from the ***real pulley experiments*** as well as **his own data** from the ***computer simulation of pulleys***.

**A)** In the first homework question, you are asked to decide what kind of pulley system would require the ***least effort force*** to lift the load. Which of the professor's data would you prefer to use? (Check **one**)

☐ Data from real pulleys ☐ Data from computer simulation of pulleys ☐ Either equally helpful

- Explain what led you to make the choice above.

**B)** In the second homework question, you are asked to decide what kind of pulley system would require the ***least work*** to lift the load. Which of the professor's data would you prefer to use? (Check **one**)

☐ Data from real pulleys ☐ Data from computer simulation of pulleys ☐ Either equally helpful

- Explain what led you to make the choice above.

Spring2010_RT

**Question 4**

If you were only going to do one pulley activity – the experiments with real pulleys or the computer simulation of pulleys – which do you think would **help you learn the best**?

☐ Real pulleys ☐ Computer simulation of pulleys ☐ Either equally helpful

- Explain what led you to make the choice above.

**Question 5**

If you could only analyze data from one of the activities – the experiments with real pulleys or the computer simulation of pulleys – which do you think you would **trust more**?

☐ Real pulleys ☐ Computer simulation of pulleys ☐ Either equally trustworthy

- Explain what led you to make the choice above.

Spring2010_RT

# Appendix M - Physical World Spring 2009: Inclined Plane Worksheet

In the Physical World Spring 2009 inclined plane study, students completed two of three activities and used physical or virtual manipulatives. The worksheets for the physical and virtual experiments are displayed in the following pages. Each worksheet includes all three activities, which involved separately changing the length, height and surface of the inclined plane. However, due to time constraints, students were only able to complete two of the three activities. Using either physical or virtual manipulatives, students completed either the length and height activities or the length and friction activities. Please note that each student completed only one worksheet packet, for either the physical or the virtual experiment.

# Inclined Plane Challenge

## *Your Challenge*:

You are borrowing a pool table from your friend to use at your birthday party. How will you get the pool table into your van to drive it to your house?

One idea is to design a ramp that will help you lift the pool table to the van since it is too heavy to carry by hand. Since we do not have a van, you will use a laundry basket and/or some books to represent the van. You will experiment with different lengths and heights of boards, types of surfaces and your mini-pool table to figure out the best ramp to reduce effort.

**We begin by exploring what you may already know about inclined planes.**

**Pages 2, 3, and the top of page 4 should be answered INDIVIDUALLY.**

**You will work with your group for the rest of this packet.**

# Anticipation Guide
# INDIVIDUALLY

*Directions*:
Read the statements below and write one of the following on the line provided before the statement:

"A" if you Agree
"D" if you Disagree
"DK" if you Don't Know

1. ______ Inclined planes are simple machines.
2. ______ An inclined plane always makes work easier.
3. ______ Inclined planes are affected by friction.
4. ______ The length of an inclined plane is important when trying to make work easier.
5. ______ If an inclined plane is high or tall, it is harder to lift things up it.
6. ______ If a surface is smooth it has more friction.
7. ______ If mechanical advantage is increased, then your effort (force) increases.

*Inclined Plane Brainstorming:*
Write down anything you know about the inclined plane. You may draw pictures along with your words.

## Predictions

**INDIVIDUALLY**: Answer the questions below. For each question, indicate your reasoning.

1. What *length* of board would best help you move the pool table into the van? Explain your choice.

2. What board *surface* would best help you move the pool table into the van? Explain your choice.

3. How will the *height* of the van affect the work needed to move the pool table into the van? Explain your reasoning.

4. Would your answers to Question 1 or Question 3 change if you had a board with ***no friction***? If so, how? Explain your reasoning

**In Your Group**: Discuss each group member's ideas and write your group's prediction below.

## Group Questions

*In a few minutes, you will research some of the science concepts related to inclined planes. Below, make a list of questions you would like to research in order to design the best ramp to move the pool table into the van? Feel free to include any "non-science" issues that may also affect your ramp choice.*

# Find out More about Inclined Planes on CoMPASS

**Go to the website www.compassproject.net. Your TA will give you the login and password.**

*Inclined Plane Challenge*: You are considering designing a ramp to help lift a pool table into the van because it is too heavy to lift by hand. You will be experimenting with different lengths of boards, types of surfaces and your mini-pool table to figure out the best possible ramp to reduce effort.
Use the CoMPASS website to explore the science concepts related to inclined planes. Use the space below to record the information you read about in CoMPASS

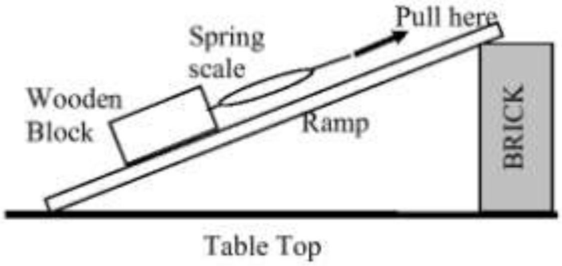
| | |
|---|---|
| | How can you design the best possible ramp to get the pool table into the van?<br>*Hints:*<br>Think about the science concepts that you need to explore to design the best possible ramp.<br>Before clicking on a concept in CoMPASS, think about how information about the concept will help you in your challenge.<br>The maps in CoMPASS will show you concepts that are related to the one you are reading. Use the maps to find out more information! |

## *Length* Experiment

We're going to model our pool table, ramp, and van with the materials on your table, as shown in the figure below. A small block will serve as the pool table, lengths of board will serve as the ramps, and a brick will serve as the van.

Use the spring scale to measure the force needed to pull the block up the ramp. Try to move the block at a constant speed while you pull.

Use the chart below to record your precise measurements and calculations. Repeat for the second board length and a vertical lift (lifting to the height of the brick with no ramp).



**Load (N) =**________________ **Height of Ramp (m) =**________________

| | **Distance Object Moves (m)** (Length of Ramp) | **Effort Force (N)** | **Work (J)** | **Ideal Mechanical Advantage (MA)** | **Actual Mechanical Advantage (MA)** | **Rank Your Best Trial** |
|---|---|---|---|---|---|---|
| Vertical Lift | | | | | | |
| Short Ramp | | | | | | |
| Long Ramp | | | | | | |

Reminder: Work = Force x Distance
$MA_{ideal}$ = Length of ramp / Height of ramp $MA_{actual}$ = Load / Effort Force

Based on the data that your group collected from the experiment, answer the questions below

1. Based on your data, when you **increase the length** of the ramp, how does it affect the **effort force** needed to move the pool table up the ramp (for a given height)?

Why do you think that is?

2. Based on your data, when you **increase the length** of the ramp, how does it affect the **work** needed to move the pool table up the ramp (for a given height)?

Why do you think that is?

3. Based on your data, when you **increase the length** of the ramp, how does it affect the **Ideal Mechanical Advantage** (for a given height)?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

Why do you think that is?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

4. Based on your data, when you **increase the length** of the ramp, how does it affect the **Actual Mechanical Advantage** (for a given height)?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

Why do you think that is?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

# *Height* Experiment

Now that you've figured out the best ramp to get the pool table into the van, the moving company has informed you that the back of the van might have a different height.

Using the available materials -- boards (ramp), spring scale, and mini-pool table you can experiment with different heights with the **long** ramp.

**Try different heights for your trials using the <u>LONG</u> ramp**. To create different heights, use the brick in different orientations. Make the tallest and shortest heights possible with the brick.

Use the chart below to record your precise measurements and calculations.

**Load (N) =**________ **Length of LONG Ramp (m):** ____________

| | **Height of Van (m)** | **Distance Object Moves (m)** (Length of Ramp) | **Effort Force (N)** | **Work (J)** | **Potential Energy (J)** | **Rank Your Best Trial** |
|---|---|---|---|---|---|---|
| Trial 1 | | | | | | |
| Trial 2 | | | | | | |

<u>Reminder</u>: Work= Force x Distance Potential Energy = Load x Height of the ramp

Based on the data that your group collected from the experiment, answer the questions below

1. Based on your data, when you **increase the height** of the ramp, how does it affect the **effort force** needed to pull the block up the ramp (for the same length)?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

Why do you think that is?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

2. Based on your data, when you **increase the height** of the ramp, how does it affect the **work** needed to pull the block up the ramp (for the same length)?

Why do you think that is?

3. Based on your data, how does **work** compare to **potential energy**?

Why do you think that is?

# *Friction* Experiment

In the real world ramps come in different varieties. In addition to length or height, another quality of a ramp that can vary is the type of surface of the ramp.

Use both sides of your long ramp to experiment with different ramp surfaces.

Record your precise measurements and calculations below.

**Load (N) =**_________ **Length of Ramp (m):** ____________

**Height of Ramp (m) =** _____________

| | **Friction** (low/high) | **Effort Force (N)** | **Work (J)** | **Potential Energy (J)** | **Ideal Mechanical Advantage (Ideal MA)** | **Actual Mechanical Advantage (Actual MA)** | **Rank Your Best Trial** |
|---|---|---|---|---|---|---|---|
| Trial 1 | Low | | | | | | |
| Trial 2 | High | | | | | | |

Reminder: Work = Effort Force x Distance Potential Energy = Load x Height

$MA_{ideal}$ = Length of ramp / Height of ramp $MA_{actual}$ = Load / Effort Force

Based on the data that your group collected from the experiment, answer the questions below

1. Based on your data, when you **increase friction**, how does it affect the **effort force** needed to pull the block up the ramp?

____________________________________________________________

____________________________________________________________

____________________________________________________________

____________________________________________________________

Why do you think that is?

____________________________________________________________

____________________________________________________________

____________________________________________________________

____________________________________________________________

2. Based on your data, when you **increase friction**, how does it affect the **work** needed to pull the block up the ramp?

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

Why do you think that is?

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

3. Based on your data, when you **increase friction**, how does it affect **Ideal mechanical advantage**?

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

Why do you think that is?

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

_________________________________________________________________________

4. Based on your data, when you **increase friction**, how does it affect **Actual mechanical advantage**?

Why do you think that is?

5. Based on your data, how does the relationship between **Ideal MA** and **Actual MA** depend on friction?

Why do you think that is?

6. Predict what would be the relationship between **Ideal MA** and **Actual MA** if the board were **frictionless**?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

____________________________________________________________________

Why do you think that is?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

7. Based on your data, how does the relationship between **Work** and **Potential Energy** depend on friction?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

Why do you think that is?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

8. Predict what would be the relationship between **Work** and **Potential Energy** if the board were **frictionless**?

Why do you think that is?

## Challenge

What would be the best way to get the pool table into the van? Explain your answer based on what you have learned from this unit.

Name: ________________________________________

Group #: _________ (Will be provided to you)

# Inclined Plane Challenge

## *Your Challenge*:

You are borrowing a pool table from your friend to use at your birthday party. How will you get the pool table into your van to drive it to your house?

One idea is to design a ramp that will help you lift the pool table to the van since it is too heavy to carry by hand. Since we do not have a van, you will use a laundry basket and/or some books to represent the van. You will experiment with different lengths and heights of boards, types of surfaces and your mini-pool table to figure out the best ramp to reduce effort.

**We begin by exploring what you may already know about inclined planes.**

**Pages 2, 3, and the top of page 4 should be answered INDIVIDUALLY.**

**You will work with your group for the rest of this packet.**

## Anticipation Guide
## INDIVIDUALLY

### *Directions*:

Read the statements below and write one of the following on the line provided before the statement:

"A" if you Agree
"D" if you Disagree
"DK" if you Don't Know

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2. ______ An inclined plane always makes work easier.
3. ______ Inclined planes are affected by friction.
4. ______ The length of an inclined plane is important when trying to make work easier.
5. ______ If an inclined plane is high or tall, it is harder to lift things up it.
6. ______ If a surface is smooth it has more friction.
7. ______ If mechanical advantage is increased, then your effort (force) increases.

### *Inclined Plane Brainstorming:*

Write down anything you know about the inclined plane. You may draw pictures along with your words.

## Predictions

**INDIVIDUALLY**: Answer the questions below. For each question, indicate your reasoning.

1. What *length* of board would best help you move the pool table into the van? Explain your choice.

2. What board *surface* would best help you move the pool table into the van? Explain your choice.

3. How will the *height* of the van affect the work needed to move the pool table into the van? Explain your reasoning.

4. Would your answers to Question 1 or Question 3 change if you had a board with *no friction*? If so, how? Explain your reasoning

**In Your Group**: Discuss each group member's ideas and write your group's prediction below.

## Group Questions

*In a few minutes, you will research some of the science concepts related to inclined planes. Below, make a list of questions you would like to research in order to design the best ramp to move the pool table into the van? Feel free to include any "non-science" issues that may also affect your ramp choice.*

# Find out More about Inclined Planes on CoMPASS

**Go to the website www.compassproject.net. Your TA will give you the login and password.**

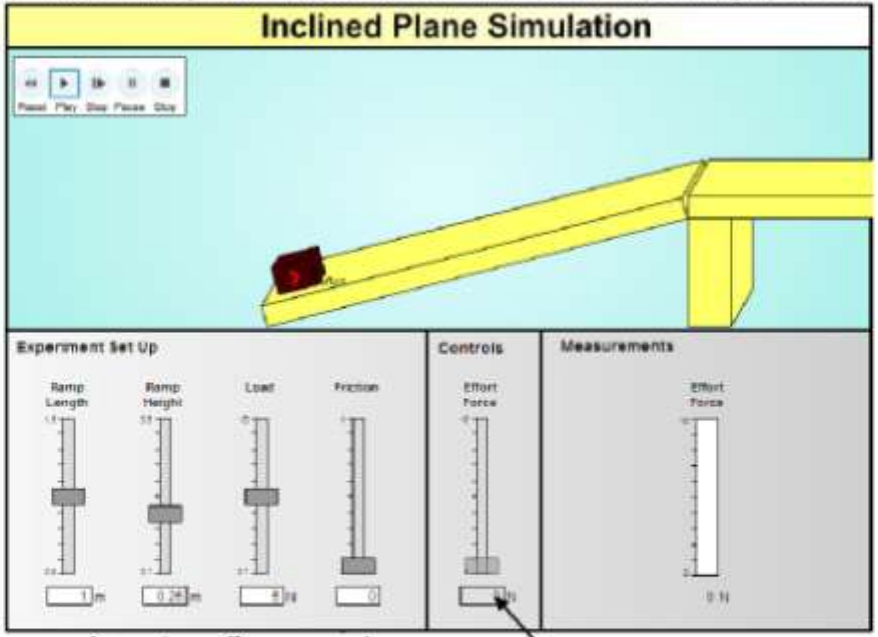
*Inclined Plane Challenge*: You are considering designing a ramp to help lift a pool table into the van because it is too heavy to lift by hand. You will be experimenting with different lengths of boards, types of surfaces and your mini-pool table to figure out the best possible ramp to reduce effort.

Use the CoMPASS website to explore the science concepts related to inclined planes. Use the space below to record the information you read about in CoMPASS

| | |
|---|---|
| | How can you design the best possible ramp to get the pool table into the van?<br>*Hints:*<br>Think about the science concepts that you need to explore to design the best possible ramp.<br>Before clicking on a concept in CoMPASS, think about how information about the concept will help you in your challenge.<br>The maps in CoMPASS will show you concepts that are related to the one you are reading. Use the maps to find out more information! |

## *Length* Simulation

We will use a computer simulation to model moving a pool table up an inclined plane. Click on the "Length" shortcut to open this simulation. You will see the screen displayed below:



Adjust these by clicking and dragging the bar or typing a number into the

**Leave friction at zero!**

Use the mouse to pull up on this bar until the block starts moving.

First, we want to explore what happens when we change the ramp's length. Input a value for the height, load, and friction. Then choose two values for the length. We will determine the effort force needed by pulling up on the effort force meter until the block just starts moving. See the hints in the screen capture above should you need assistance.

Record the effort force and calculate the other values in the table below.

**Load (N) =** ____________

| **Type of Ramp** | **Distance Object Moves (m)** (Length of Ramp) | **Effort Force (N)** | **Work (J)** | **Ideal Mechanical Advantage (MA)** | **Actual Mechanical Advantage (MA)** | **Rank Your Best Trial** |
|---|---|---|---|---|---|---|
| Short Ramp | | | | | | |
| Long Ramp | | | | | | |

Reminder: Work = Effort Force x Distance

$MA_{actual}$ = Load / Effort Force

$MA_{ideal}$ = Length of ramp / Height of ramp

Based on the data that your group collected from the simulation, answer the questions below

1. Based on your data, when you **increase the length** of the ramp, how does it affect the **effort force** needed to move the pool table up the ramp (for a given height)?

Why do you think that is?

2. Based on your data, when you **increase the length** of the ramp, how does it affect the **work** needed to move the pool table up the ramp (for a given height)?

Why do you think that is?

3. Based on your data, when you **increase the length** of the ramp, how does it affect the **Ideal Mechanical Advantage** (for a given height)?

Why do you think that is?

4. Based on your data, when you **increase the length** of the ramp, how does it affect the **Actual Mechanical Advantage** (for a given height)?

Why do you think that is?

5. What do you think is the **effort force** needed to lift the pool table into the van without the use of a ramp?

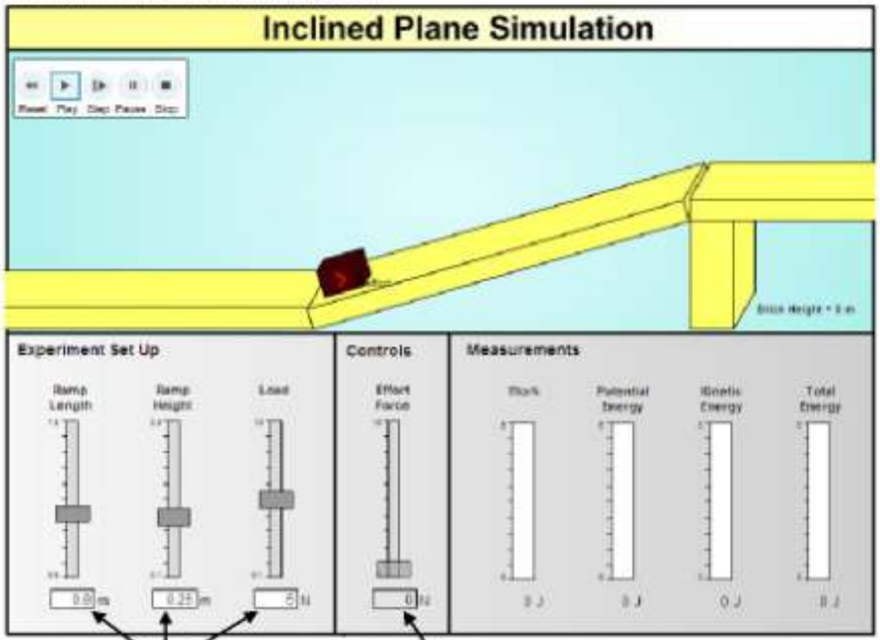
Why do you think that is?

6. What do you think is the **work** needed to lift the pool table into the van without the use of a ramp?

Why do you think that is?

## *Height* Simulation

Now, you will use the inclined plane simulation to explore what would happen if we needed to move the pool tale into vans of different heights. Click on the "Height" shortcut to open this simulation. You will see the screen below:



Adjust these by clicking and dragging bar or typing a number into the box.

Use the mouse to pull up on this bar until the block starts moving.

Input a value for the length, load, and friction. Then choose two values for the height. We will determine the effort force needed by pulling up on the effort force meter until the block just starts moving. See the hints in the screen capture above should you need assistance. This simulation also displays values for the work, potential energy, kinetic energy, and total energy for the block as it moves up the ramp.

Record your measurements and calculations in the table below.

**Load (N) =**________ **Length of Ramp (m) =** _________

| | Height of Van (m) | Distance Object Moves (m) (Length of Ramp) | Effort Force (N) | Work (J) | Potential Energy (J) | Rank Your Best Trial |
|---|---|---|---|---|---|---|
| Trial 1 | | | | | | |
| Trial 2 | | | | | | |

Reminder: Work= Force x Distance Potential Energy = Load x Height of the ramp

Based on the data that your group collected from the simulation, answer the questions below

1. Based on your data, when you **increase the height** of the ramp, how does it affect the **effort force** needed to pull the block up the ramp (for the same length)?

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

Why do you think that is?

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

2. Based on your data, when you **increase the height** of the ramp, how does it affect the **work** needed to pull the block up the ramp (for the same length)?

Why do you think that is?

3. Based on your data, how does **work** compare to **potential energy**?

Why do you think that is?

## *Friction* Simulation

Now, we will use the "Length" simulation again, but this time you will explore what happens when we have surfaces with different amounts of friction. Enter values for the length, height, and load. Then, choose three values for your friction: zero, a number close to zero (low friction), and a number close to one (high friction). Use the simulation to find the effort force needed to pull the pool table up the ramp with each value of friction. Then, calculate the rest of the quantities in the table below.

**Load (N) =**________ **Short Ramp Length (m) =** ________ **Height (m) =**________

| | **Friction** (Zero / Low / High) | **Effort Force (N)** | **Work (J)** | **Potential Energy (J)** | **Ideal Mechanical Advantage (MA)** | **Actual Mechanical Advantage (MA)** | **Rank Your Best Trial** |
|---|---|---|---|---|---|---|---|
| Trial 1 | | | | | | | |
| Trial 2 | | | | | | | |
| Trial 3 | | | | | | | |

Reminder: Work = Effort Force x Distance Potential Energy = Load x Height

$MA_{ideal}$ = Length of ramp / Height of ramp $MA_{actual}$ = Load / Effort Force

Based on the data that your group collected from the simulation, answer the questions below

1. Based on your data, when you **increase friction**, how does it affect the **effort force** needed to pull the block up the ramp?

Why do you think that is?

2. Based on your data, when you **increase friction**, how does it affect the **work** needed to pull the block up the ramp?

Why do you think that is?

3. Based on your data, when you **increase friction**, how does it affect **Ideal mechanical advantage**?

Why do you think that is?

4. Based on your data, when you **increase friction**, how does it affect **Actual mechanical advantage**?

Why do you think that is?

5. Based on your data, how does the relationship between **Ideal MA** and **Actual MA** depend on friction?

Why do you think that is?

## Challenge

What would be the best way to get the pool table into the van? Explain your answer based on what you have learned from this unit.

How did the simulation's conditions differ from those you would encounter with a real-life ramp and pool table?

# Appendix N - Physical World Spring 2009: Inclined Plane Test

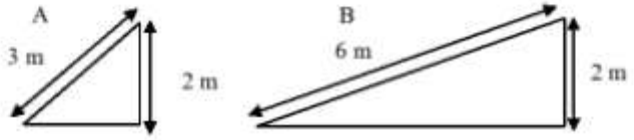
The test used in the Physical World Spring 2009 inclined plane study is included on the following pages. Students took the test before receiving any instruction on inclined planes (as a pre-test) and after completing their activities (as a post-test).

Name: ______________________________________________

## Inclined Planes Post Test

Instructions: Circle only *one* letter to indicate your answer for each question.

1) Which of the following two ramps will require *less effort* (force) to ride up, if the effect of friction is the same for both ramps?



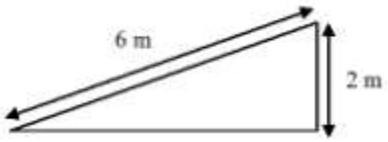
A. Ramp A

B. Ramp B

C. Both A and B will require the same *effort* (force) to ride up

D. Not enough information to decide

2) What will require *less effort* (force) to lift a box to a height of 2 meters – using the ramp shown or lifting the box straight up?



A. Using the ramp

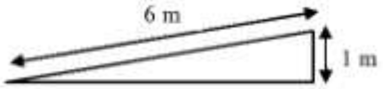
B. Lifting it straight up

C. Using the ramp or lifting it straight up will both require the same effort (force)

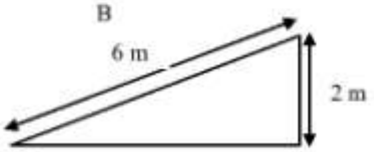
D. Not enough information to decide

3) Which of the following ramps will require *less effort* (force) to ride up, if the effect of friction is the same for both ramps?

A



B



A. Ramp A

B. Ramp B

C. Both A and B will require the same *effort* (force) to ride up

D. Not enough information to decide

4) Which of the following will require *less effort* (force) to lift a load to a height of 2 meters using a ramp that is 5 meters in length?

A. A ramp that has a smooth surface

B. A ramp that has a rough surface

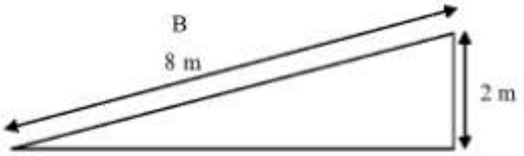
C. Both ramps will require the same *effort* (force)

D. Not enough information to decide

5) Which of the following ramps will require *less effort* (force) to ride up, if the effect of friction is the same for both ramps?

A

B



A. Ramp A

B. Ramp B

C. Both A and B will require the same effort force to ride up

D. Not enough information to decide

6a) You used a 5 meter long ramp with no friction to move an object into a van. If you were to use a 10 meter long ramp with no friction to move the object into the same van, the *effort* (force) needed would:

*Circle one*:

A. Increase
B. Decrease
C. stay the same
D. not enough information to decide

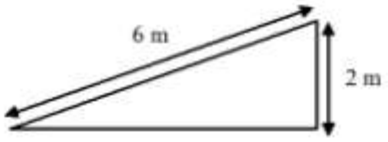
and the *work* done would:

*Circle one*:

A. Increase
B. Decrease
C. stay the same
D. not enough information to decide

6b) Explain your reasoning for both *effort* (force) and *work*.

7) Jane is lifting a box straight up to a height of 2 meters. Mary is using the ramp shown below. If friction is not a factor, what can you tell about the *work done* by Jane and Mary?



A. Jane is doing more work
B. Mary is doing more work
C. Jane and Mary are doing the same work
D. Not enough information to decide

8) Chris wants to use a ramp to move a box into his van. Which of the following will require *less work* for Chris to move the box to the same height?

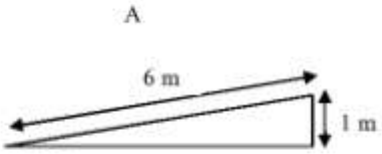
A. A ramp that has a smooth surface

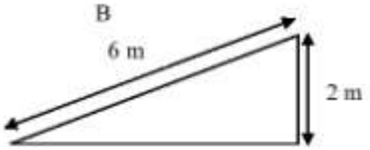
B. A ramp that has a rough surface

C. Both ramps will require the same work

D. Not enough information to decide

9) If both ramps have no friction, what can you tell about the *work* done to push a box to the top of the ramps?





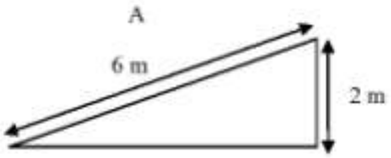
A. More work is required for Ramp A

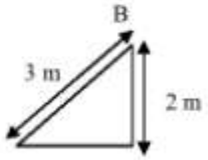
B. More work is required for Ramp B

C. Ramp A and Ramp B would require the same work

D. Not enough information to decide

10) Which of the following two ramps will give you more *mechanical advantage* (MA), if the effect of friction is the same for both ramps?





A. Ramp A

B. Ramp B

C. Both A and B will give you the same *mechanical advantage* (MA)

D. Not enough information to decide

11) Which of the following ramps will give more *mechanical advantage (MA)* to lift a load to a height of 3 meters, if the effect of friction is the same for both ramps?

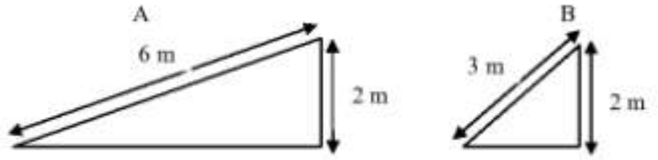
A. A ramp that is 9 m in length

B. A ramp that is 27 m in length

C. Both ramps will have the same *mechanical advantage (MA)*

D. Not enough information to decide

12) Louis pushes a box to the top of Ramp A. Toby pushes a box to the top of Ramp B. Which box has *more potential energy* when it gets to the top if the ramp?



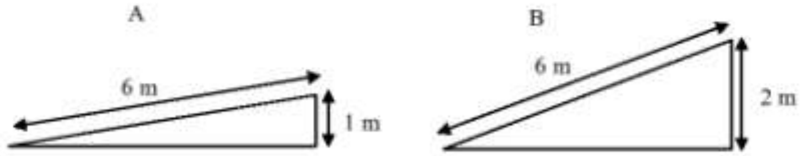
A. The box on Ramp A

B. The box on Ramp B

C. Both boxes have the same potential energy

D. Not enough information to decide

13) Diane pushes a box to the top of Ramp A. Fran pushes the same box to the top of Ramp B. Which box has *more potential energy* when it gets to the top if the ramp?



A. The box on Ramp A

B. The box on Ramp B

C. Both boxes have the same potential energy

D. Not enough information to decide

14) An object sits at the top of a frictionless ramp. How does the object's potential energy compare to the work required to move it to the top of the ramp?

A. The object's potential energy is greater than the required work.
B. The object's potential energy is less than the required work.
C. The object's potential energy is the same as the required work
D. Not enough information to decide.

15) How does an inclined plane's actual mechanical advantage (MA) compare to its ideal mechanical advantage (MA)?

A. Ideal MA is always greater than Actual MA
B. Ideal MA is always less than Actual MA
C. Ideal MA can be equal to or less than Actual MA
D. Ideal MA can be equal to or greater than Actual MA

# Appendix O - Physical World Fall 2009: Inclined Plane Worksheet

In the Physical World Fall 2009 inclined plane study, students completed experiments to investigate the effects changing the length, height and surface of the inclined plane. Students completed the experiments with both physical and virtual manipulatives, but in different sequences. The worksheet on the following pages was used by students who completed the experiments in the physical-virtual sequence.

LAST NAME (ALL CAPS): ___________________________

FIRST NAME (ALL CAPS): __________________________

Group #: ______________________ (TA will provide)

## Inclined Plane Challenge

### *Your Challenge*:

You are borrowing a pool table from your friend to use at your birthday party. How will you get the pool table into your van to drive it to your house?

One idea is to design a ramp that will help you lift the pool table to the van since it is too heavy to carry by hand. Since we do not have a van, you will use a laundry basket and/or some books to represent the van. You will experiment with different lengths and heights of boards, types of surfaces and your mini-pool table to figure out the best ramp to reduce effort.

**We begin by exploring what you may already know about inclined planes.**

**Pages 2, 3, and the top of page 4 should be answered INDIVIDUALLY.**

**You will work with your group for the rest of this packet.**

## Anticipation Guide
## INDIVIDUALLY

*Directions*:

Read the statements below and write one of the following on the line provided before the statement:

"A" if you Agree
"D" if you Disagree
"DK" if you Don't Know

1. ______ Inclined planes are simple machines.
2. ______ An inclined plane always makes work (input) easier.
3. ______ Inclined planes are affected by friction.
4. ______ The length of an inclined plane is important when trying to make work (input) easier.
5. ______ If an inclined plane is high or tall, it is harder to lift things up it.
6. ______ If a surface is smooth it has more friction.
7. ______ If mechanical advantage is increased, then your effort (force) increases.

*Inclined Plane Brainstorming:*

Write down anything you know about the inclined plane. You may draw pictures along with your words.

# Predictions

**INDIVIDUALLY**: Answer the questions below. For each question, indicate your reasoning.

1. What *length* of board would best help you move the pool table into the van? Explain your choice.

2. What board *surface* would best help you move the pool table into the van? Explain your choice.

3. How will the *height* of the van affect the work (input) needed to move the pool table into the van? Explain your reasoning.

**4.** Would your answers to Question 1 or Question 3 change if you had a board with ***no friction***? If so, how? Explain your reasoning.

**In Your Group**: Discuss each group member's ideas and write your group's prediction below.

## Group Questions

*In a few minutes, you will research some of the science concepts related to inclined planes. Below, make a list of questions you would like to research in order to design the best ramp to move the pool table into the van? Feel free to include any "non-science" issues that may also affect your ramp choice.*

## Find out More about Inclined Planes on CoMPASS

**Go to the website www.compassproject.net.**

**Use the Group # as login name and password**

*Inclined Plane Challenge*: You are considering designing a ramp to help lift a pool table into the van because it is too heavy to lift by hand. You will be experimenting with different lengths of boards, types of surfaces and your mini-pool table to figure out the best possible ramp to reduce effort.
Use the CoMPASS website to explore the science concepts related to inclined planes. Use the space below to record the information you read about in CoMPASS.

| | |
|---|---|
| | How can you design the best possible ramp to get the pool table into the van?<br>*Hints:*<br>Think about the science concepts that you need to explore to design the best possible ramp.<br>Before clicking on a concept in CoMPASS, think about how information about the concept will help you in your challenge.<br>The maps in CoMPASS will show you concepts that are related to the one you are reading. Use the maps to find out more information! |

6

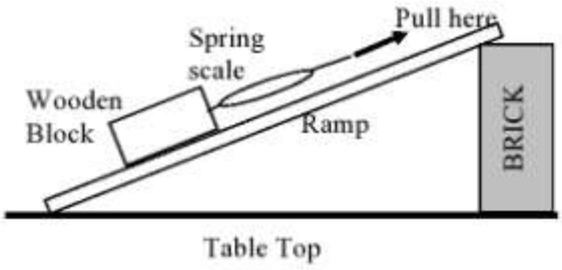
P-of-PV-F09-YELLOW

## Physical Experiments

We're going to model our pool table, ramp, and van with the materials on your table, as shown in the figure below. A small block will serve as the pool table, wooden boards will serve as the ramps, and a brick will serve as the van.

Use the spring scale to measure the force needed to pull the block up the ramp. Try to move the block at a constant speed while you pull.

Use the table on the next page to record your precise measurements and calculations.



**Trial 1 (Initial Set-up):** Using the long board, choose a height for the "van" (i.e. brick) and a surface (wood or wax – do not use sandpaper). Pull the block up at a constant speed. Record your measurements and calculations in the table. (Note: subsequent experimental trials will be based on this set-up.)

**Trial 2 (Change Length)** Repeat the experiment using a set-up similar to Trial 1, except use a board with a different length. Record your measurements and calculations in the table.

**Trial 3 (Change Height)** Repeat the experiment using a set-up similar to Trial 1, except change the orientation of the brick so that you're lifting the load to a different height (i.e. like changing the height of the van). Record your measurements and calculations in the table.

**Trial 4 (Change Friction)** Repeat the experiment using a set-up similar to Trial 1, except change the surface (wood, wax or sandpaper) so that is has a different amount of friction. Record your measurements and calculations in the table.

**Additional Trials** You may decide to do additional experimental trials to help you answer the questions following the experiments. Use the table to record measurements/calculations for additional experimental trials.

**Hang the load vertically from the spring scale and measure it. Record it below.**

**Load (N) =**__________________

Measure these using the ruler

Select based on your surface

Measure using spring scale

Calculate these using formulae below

| | **Distance Object Moves (m)** *Ramp Length* | **Height of Van (m)** | **Friction (low/ medium/ high)** | **Effort Force (N)** | **Work (input) (J)** | **Potential Energy (at top of ramp) (J)** | **Ideal Mechanical Advantage (MA)** | **Actual Mechanical Advantage (MA)** |
|---|---|---|---|---|---|---|---|---|
| **Trial 1** | | | | | | | | |
| **Trial 2** change *Length* | | | | | | | | |
| **Trial 3** change *Height* | | | | | | | | |
| **Trial 4** change *Friction* | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |

**Formulae**: Work (input) = Effort Force x Distance

Potential Energy = Load x Height

Ideal Mechanical Advantage = Length of ramp / Height of ramp

Actual Mechanical Advantage = Load / Effort Force

Based on the data that your group collected from the experiment, answer the questions below:

1. How does the ***effort force*** needed to move the load change if the:

*length* of the ramp **increases**?____________________________________________

*height* of the ramp **increases**?____________________________________________

*surface* of the ramp gets **rougher**?__________________________________________

**2.** How does the ***work (input)*** needed to move the load change if the:

*length* of the ramp **increases**?____________________________________________

*height* of the ramp **increases**?____________________________________________

*surface* of the ramp gets **rougher**?__________________________________________

**3.** How does the ***potential energy*** of the load at the top of the ramp change if the:

*length* of the ramp **increases**?

*height* of the ramp **increases**?

*surface* of the ramp gets **rougher**?

**4.** Below you are asked to ***compare work (input)*** and ***potential energy*** in different conditions.

a. How does the *work (input)* and *potential energy* compare when there **is friction**?

b. How does the relationship between *work (input)* and *potential energy* change as the surface gets **smoother**?

c. How would *work (input)* and *potential energy* compare if there were **no friction**?

**5.** How does the ***ideal mechanical advantage*** change if the:

*length* of the ramp **increases**?____________________

*height* of the ramp **increases**?____________________

**surface** of the ramp gets **rougher**?____________________

**6.** How does the ***actual mechanical advantage*** change if the:

*length* of the ramp **increases**?____________________

*height* of the ramp **increases**?____________________

*surface* of the ramp gets **rougher**?____________________

**Please ask the TA for the Mid-Test**

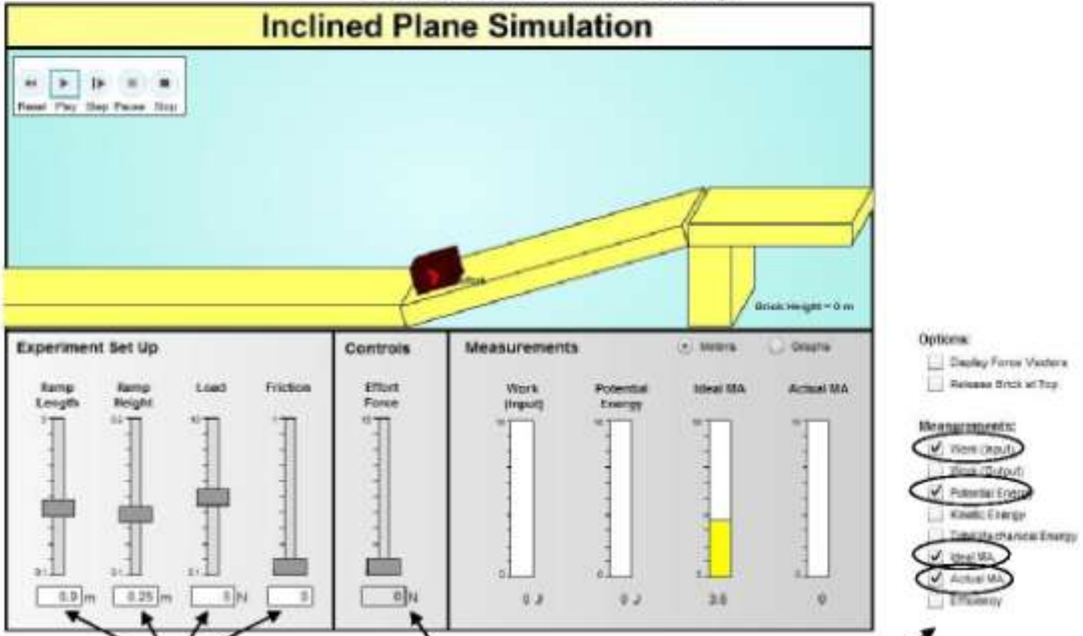
LAST NAME (ALL CAPS): ___________________________

FIRST NAME (ALL CAPS): __________________________

Group #: ______________________ (TA will provide)

# Virtual Experiment

You will use an online simulation to model moving a pool table up an inclined plane.
Click on the icon on the desktop



Ramp Length: 0.9 m
Ramp Height: 0.25 m
Load: 5 N
Friction: 0
Effort Force: 0 N
Work (Input): 0 J
Potential Energy: 0 J
Ideal MA: 3.6
Actual MA: 0

Options:
☐ Display Force Vectors
☐ Release Brick at Top

Measurements:
☑ Work (Input)
☐ Work (Output)
☑ Potential Energy
☐ Kinetic Energy
☐ Total Mechanical Energy
☑ Ideal MA
☑ Actual MA
☐ Efficiency

Adjust these by clicking and dragging bar or typing a number into the box.

Use the mouse to pull up on this bar until the block starts moving.

Make sure that the boxes here are checked as shown above.

Use the table on the next page to record the values of each quantity for each experiment.

**Trial 1 (Initial Set-up):** Choose a length for the ramp and a height for the "van" (i.e. brick). Set the friction equal to zero. Pull up on the effort force meter until the block just starts moving. Record the relevant values (i.e. your data) in the table.

**Trial 2 (Change Length)** Repeat the experiment using a set-up similar to Trial 1, except use a different ramp length. Record your data in the table.

**Trial 3 (Change Height)** Repeat the experiment using a set-up similar to Trial 1, except change the ramp height so that you're lifting the load to a different height (i.e. like changing the height of the van). Record your measurements and calculations in the table.

**Trial 4 (Change Friction)** Repeat the experiment using a set-up similar to Trial 1, except change the friction. Record your measurements and calculations in the table.

**Additional Trials** You may decide to do additional experimental trials to help you answer the questions following the experiments. Use the table to record measurements/calculations for additional experimental trials.

**Record the Load from the Experiment Setup section of the simulation screen**

**Load (N) =________________**

Read these off the 'Experiment Set Up'

Read this off the 'Controls'

Read these off the numbers below the bar charts in the 'Measurements'

| | **Distance Object Moves (m)** *Ramp Length* | **Height of Van (m)** | **Friction** | **Effort Force (N)** | **Work (input) (J)** | **Potential Energy (at top of ramp) (J)** | **Ideal Mechanical Advantage (MA)** | **Actual Mechanical Advantage (MA)** |
|---|---|---|---|---|---|---|---|---|
| **Trial 1** | | | | | | | | |
| **Trial 2** change *Length* | | | | | | | | |
| **Trial 3** change *Height* | | | | | | | | |
| **Trial 4** change *Friction* | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |

Based on the data that your group collected from the simulation, answer the questions below:

**1.** How does the ***effort force*** needed to move the load change if the:

*length* of the ramp **increases**?______________________________

*height* of the ramp **increases**?______________________________

*surface* of the ramp gets **rougher**?______________________________

**2.** How does the ***work (input)*** needed to move the load change if the:

*length* of the ramp **increases**?______________________________

*height* of the ramp **increases**?______________________________

*surface* of the ramp gets **rougher**?______________________________

3. How does the ***potential energy*** of the load at the top of the ramp change if the:

*length* of the ramp **increases**?________________________________________

*height* of the ramp **increases**?________________________________________

*surface* of the ramp gets **rougher**?______________________________________

**4.** Below you are asked to ***compare work (input)*** and ***potential energy*** in different conditions.

a. How does the *work (input)* and *potential energy* compare when there **is friction**?

b. How does the relationship between *work (input)* and *potential energy* change as the surface gets **smoother**?

c. How does *work (input)* and *potential energy* compare when there is **no friction**?

**5.** How does the ***ideal mechanical advantage*** change if the:

*length* of the ramp **increases**?______________________________

______________________________________________

______________________________________________

*height* of the ramp **increases**?______________________________

______________________________________________

______________________________________________

**surface** of the ramp gets **rougher**?___________________________

______________________________________________

______________________________________________

**6.** How does the ***actual mechanical advantage*** change if the:

*length* of the ramp **increases**?______________________________

______________________________________________

______________________________________________

*height* of the ramp **increases**?______________________________

______________________________________________

______________________________________________

*surface* of the ramp gets **rougher**?___________________________

______________________________________________

______________________________________________

## Challenge

**7.** What would be the best way to get the pool table into the van? Explain your answer based on what you have learned from this unit.

**8.** How did the *physical experiment's* conditions differ from what you would encounter with a real-life ramp and pool table?

**9.** How did the *simulation's* conditions differ from what you would encounter with a real-life ramp and pool table?

# Appendix P - Physical World Fall 2009: Inclined Plane Test

The test used in the Physical World Fall 2009 inclined plane study is included on the following pages. Students took the test before receiving any instruction on inclined planes (as a pre-test), in between the physical and virtual experiments (as a mid-test), and after completing both experiments (as a post-test).

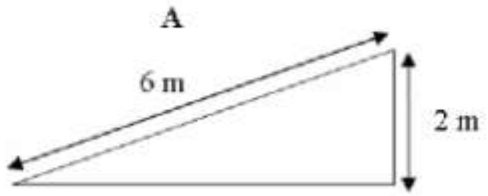
**LAST NAME (ALL CAPS)** ______________________________

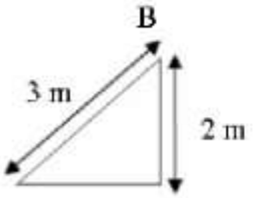
**FIRST NAME (ALL CAPS)** ______________________________

## Inclined Planes Post-Test

**Instructions**: Circle only *one* letter to indicate your answer for each question.

**Q01**) If we ignore friction, which of the following two ramps will require *less effort* (force) to ride up?





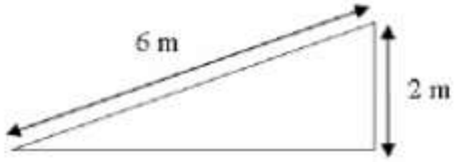
A.) Ramp A

B.) Ramp B

C.) Both A and B will require the same effort (force) to ride up

D.) Not enough information to decide

**Q02**) If we ignore friction, what will require *less effort* (force) to lift a box to a height of 1 meter – using the ramp shown or lifting the box straight up?



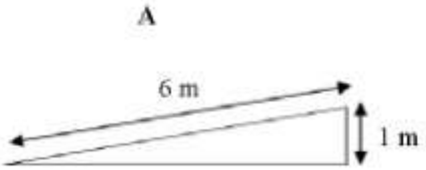
A.) Using the ramp

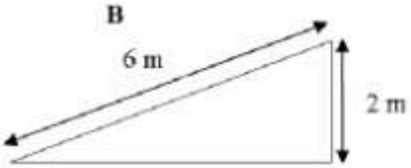
B.) Lifting it straight up

C.) Using the ramp or lifting it straight up will both require the same effort (force)

D.) Not enough information to decide

**Q04**) If we ignore friction, which of the following ramps will require *less effort* (force) to ride up?





A.) Ramp A

B.) Ramp B

C.) Both A and B will require the same effort (force) to ride up

D.) Not enough information to decide

**Q05**) Which of the following will require *less effort* (force) to lift a load to a height of 2 m using a ramp that is 5 m in length?

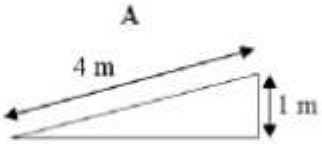
A.) A ramp that has a smooth surface

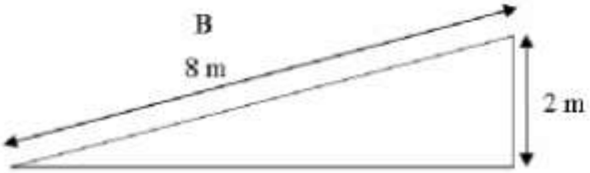
B.) A ramp that has a rough surface

C.) Both ramps will require the same effort (force)

D.) Not enough information to decide

**Q06**) If we ignore friction, which of the following ramps will require *less effort* (force) to ride up?





A.) Ramp A

B.) Ramp B

C.) Both A and B will require the same effort (force) to ride up

D.) Not enough information to decide

**Q08**) You used a 5 meter long ramp to move an object into a van. If you used a 10 meter long ramp instead to move the object into the same van and ignore the effects of friction:

**Q08a-1**) the *effort* (force) needed would:

*Circle one*:

A.) Increase

B.) Decrease

C.) stay the same

D.) not enough information to decide

**Q08a-2**) Explain your reasoning about the *effort* (force) needed.

**Q08b-1**) and the *work (input)* done would:

*Circle one*:

A.) Increase

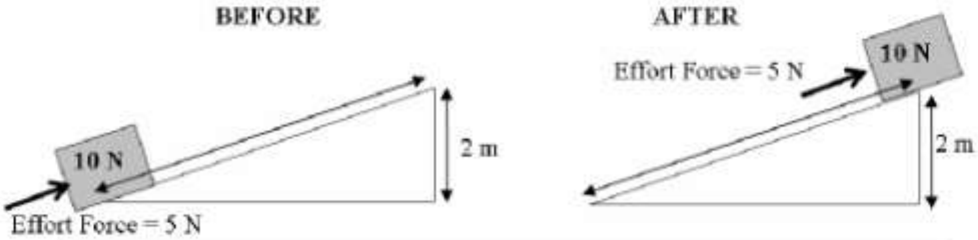
B.) Decrease

C.) stay the same

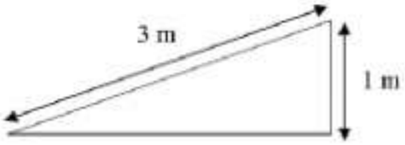
D.) not enough information to decide

**Q08b-2**) Explain your reasoning about the *work (input)* done.

**Q09**) Below are before and after pictures of a 10N load being lifted with the help of a ramp. Ignoring friction, calculate the *work (input)* done to lift a load to the top of the ramp using the information from the picture below:



**Q10**) Jane is lifting a box straight up to a height of 2 m. Mary is using the ramp shown below to lift the same box to the same height. If we ignore friction, what can you tell about the *work(input)* by Jane and Mary?



A.) Jane is doing more work

B.) Mary is doing more work

C.) Jane and Mary are doing the same work

D.) Not enough information to decide

**Q10a**) Explain your reasoning about *work (input)* in this question.

**Q11**) Which of the following with require more *work (input)* to lift a load to a height of 2 m using a ramp?

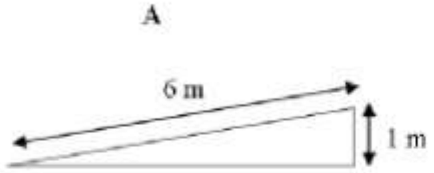
A.) A ramp that has a smooth surface

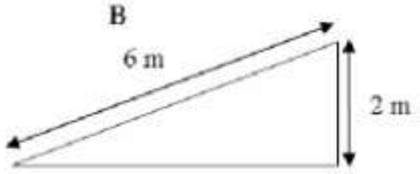
B.) A ramp that has a rough surface

C.) Both ramps will require the same work

D.) Not enough information to decide

**Q12**) Jacob is using ramps to lift two boxes of the same size and mass up to two different heights. He lifts one box to the top of Ramp A and then lifts the second box to the top of Ramp B. Ignoring friction, when lifting the box to the top of Ramp B Jacob is doing _______ *work (input)* as/than when lifting the box to the top of ramp A?





A.) More

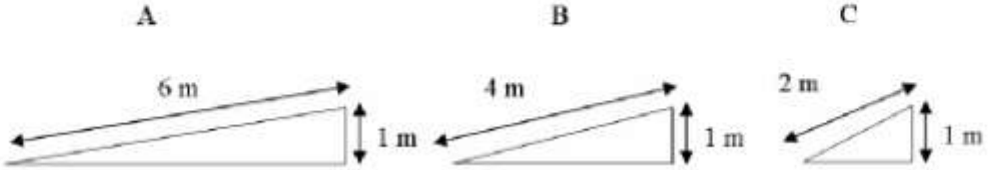
B.) Less

C.) Same amount of

D.) Not enough information to decide

**Q12a**) Explain your reasoning about *work (input)* in this question.

**Q13)** Amy is using Ramp A, Bob is using Ramp B, and Cathy is using Ramp C. What can you tell about the *work (input)* needed to lift the same load to the top of each ramp, if we ignore friction?



A.) Amy (using Ramp A) is doing more work (input)

B.) Bob (using Ramp B) is doing more work (input)

C.) Cathy (using Ramp C) is doing more work (input)

D.) The work (input) done in all three situations is the same

**Q14)** If we ignore friction, which of the following ramps will give more *mechanical advantage* to lift a load to a height of 3 m?

A.) A ramp that is 9 m in length

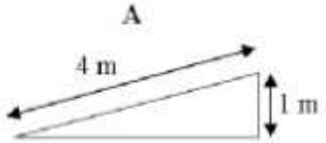
B.) A ramp that is 27 m in length

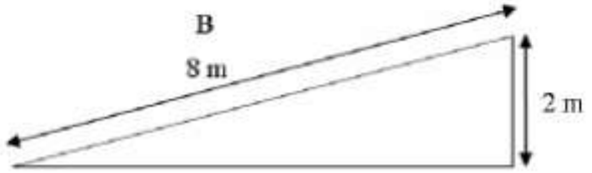
C.) Both ramps will have the same mechanical advantage

D.) Not enough information to decide

**Q14a)** Explain your reasoning about *mechanical advantage* in this question.

**Q15**) If we ignore friction, which of the following ramps will give more *mechanical advantage*?





A.) Ramp A

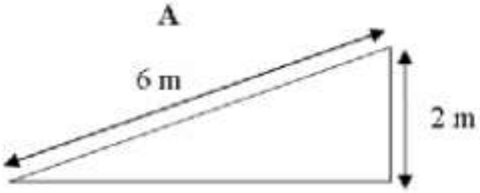
B.) Ramp B

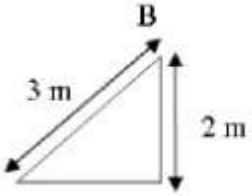
C.) Both A and B will give you the same mechanical advantage

D.) Not enough information to decide

**Q15a**) Explain your reasoning about *mechanical advantage* in this question.

**Q16**) If we ignore friction, which of the following two ramps will give you more *mechanical advantage*?





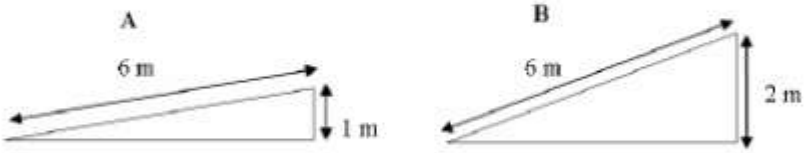
A.) Ramp A

B.) Ramp B

C.) Both A and B will give you the same mechanical advantage

D.) Not enough information to decide

**Q17)** Diane pushes a box to the top of Ramp A. Fran pushes the same box to the top of Ramp B. Which box undergoes *a greater change in potential energy*?



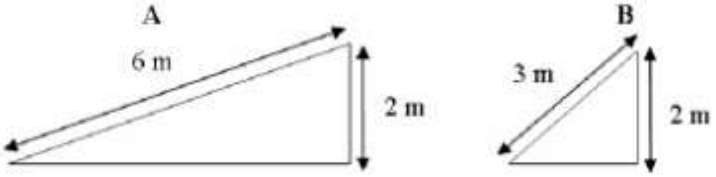
A.) The box on Ramp A

B.) The box on Ramp B

C.) Both boxes have the same potential energy

D.) Not enough information to decide

**Q18)** Louis pushes a box to the top of Ramp A. Toby pushes a box to the top of Ramp B. Which undergoes *a greater change in potential energy*?



A.) The box on Ramp A

B.) The box on Ramp B

C.) Both boxes have the same change in potential energy

D.) Not enough information to decide

**Q19)** Henry uses a very smooth ramp to lift a box 1 m. If you can ignore friction, how does the *work (input)* to lift the box compare to the box's *change in potential energy* while being lifted?

A.) The work (input) needed is greater than the change in potential energy

B.) The work (input) needed is less than the change in potential energy

C.) The work (input) needed is the same as the change in potential energy

D.) Not enough information to decide

**Q20)** Gloria uses a ramp with a rough surface to lift a box 1 m. If you cannot ignore friction, how does the *work (input)* to lift the box compare to the box's *change in potential energy* while being lifted?

A.) The work (input) needed is greater than the change in potential energy

B.) The work (input) needed is less than the change in potential energy

C.) The work (input) needed is the same as the change in potential energy

D.) Not enough information to decide

# Appendix Q - Inclined Plane Interview Protocol

In Fall 2009, learning/teaching interviews were conducted to investigate how the environment created by the physical and virtual manipulatives supported students in building their understanding of the physics of inclined planes. Each interview followed the same overall framework, detailed in the interview protocol on the following pages. However, the specific follow-up questions asked varied based on the students' responses to the over-arching challenge questions.

Virtual/Physical Teaching Interview Protocol
November, 2009

Overall goals:

1. Gather data on how the physical and virtual environments each support or impede dynamic transfer.
2. Determine what kind of scaffolding from the interviewer supports additional dynamic transfer.
3. Trace the conceptual resources gained as student's progress through activity.
    a. Sub-goal: establishing qualitative relationships between concepts

## 1. Present the challenge

Challenge "You work for a moving company and your job is to advise people about ramps they can use to move their stuff into a moving truck. As part of your training, you need to come up with a set of guiding rules for advising customers. So, your challenge here is to develop a set of guiding rules for advising customers about ramps."

Before you come up with your set of guiding rules, what will you need to know in order to advise the customers? [ask each part of this question separately]

What questions would you like to ask the customer?

What would you like to know about your company's equipment?

What are your initial ideas about what some of the guiding rules might be?

Can think of any science ideas that are related to these initial ideas?

What questions would you need to ask in order to create guiding rules based on science ideas? Could you please write a list?

## 2. CoMPASS

What questions would you like to ask an expert in order to help you with this challenge? Can you write down a list?

Now you will have a chance to answer some of your questions and further explore some of the science ideas related to your challenge using a website called CoMPASS.

The concept maps here are designed to help you see connections between different concepts. The distance between boxes represents how closely the concepts are related. The links between boxes show which concepts are related to which other concepts. The back button doesn't work for navigation, but you can use the history.

As you explore, please talk about information you find related to your questions or the challenge in general. It would be most helpful if you would talk about this each time you transition from one page to another.

Feel free to take notes about what you learn. These will be useful later for the challenge.

** We need to ask her more about why she clicked on something and what she got from it that would pertain to the questions she had posed earlier
** Which item do you think you might want to click on that pertains to the challenge?
** Any other concepts that are unfamiliar
** Is there was anything here that would help you make the guiding rules?
** Can you use anything you learned on CoMPASS to help demonstrate to the boss?

## 3. Simulation or Physical Activity

Here is a simulation that you can use to explore and develop your ideas and answer any questions you still have.

**Changed wording because they seemed to be in a position of authority over ideas that they didn't have authority over.
**Let students do whatever they like at this point. Ask clarifying questions about what they are doing and why they are doing it, but don't ask anything that would shape what they are doing. No scaffolding at this point.
**When students seem to finish, begin asking the mini challenge questions listed below. Build scaffolding as necessary to help the students complete the mini challenges.

Suppose you were now to use this simulation to demonstrate your ideas to the boss. If I am your boss, how would you use the simulation to show me that your ideas are correct.

Goal 1 – slope decreases, so does force (science goal)
*keep height constant, but change length and look at force (idea of experiment to do)
Ask: Your company uses a motor to pull objects up a ramp. A rope connects the motor and object being moved. If you were given a moving truck and a rope that has a maximum force tolerance, how can you figure out which ramps to use?

Can you summarize your ideas for this question?

Goal 2 – energy used (fuel) depends on height only for frictionless (smooth ramps)
for two different heights, change lengths and look at potential energy and work
Ask: Given several different moving trucks, smooth ramps and a given load, how can you predict how much the electric bill would be to move the object?
Can you summarize your ideas for this question?

Goal 3 – With friction, work done (fuel) is more than the change in potential energy (change in height)
*Add friction, and for two different heights, change lengths and look at potential energy & work.

Ask: Given several different moving trucks, rough ramps and a given load, how can you predict how much the electric bill would be?

Can you summarize your ideas for this question?

Goal 4 – fuel used (work) depends on the product of length and force
*without friction, keeping height the same, for a given amount of force, the work will increase with distance
Ask: Given a specific truck, smooth ramps, and a rope with a certain force tolerance, how can you predict how much the electric bill will be with different length ramps?

Can you summarize your ideas for this question?

Goal 5 – load to effort force ratio depends on steepness of ramp (mechanical advantage)
*look at ratio
ASK: Suppose you had chosen a certain length for a certain height truck. On moving day, it turns out you have to use a truck that is twice as high. How could you quickly predict the best length of ramp to use?

Can you summarize your ideas for this question?

## 4. Summary

Can you please summarize all of your ideas about how to best use the companies supplied to meet the customers needs?

If the student (using sim) has used only one of the views (meters or graphs) show the other and ask what the advantages/disadvantages of each are.

Ask the student how the sim is different from the real world.

Ask the student about the advantages and disadvantages of doing a physical experiment and using the simulation.