RELATIONSHIPS BETWEEN UNDERGRAUATES’ ARGUMENTATION SKILLS, CONCEPTUAL QUALITY OF PROBLEM SOLUTIONS, AND PROBLEM SOLVING STRATEGIES IN INTRODUCTORY PHYSICS

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the dissertation entitled

RELATIONSHIP BETWEEN UNDERGRADUATES' ARGUMENTATION SKILLS, CONCEPTUAL QUALITY OF PROBLEM SOLUTIONS, AND PROBLEM SOLVING STRATEGIES IN INTRODUCTORY PHYSICS

Presented by Carina M. Rebello,

A candidate for the degree of Doctor of Philosophy.

And hereby certify that, in their opinion, it is worthy of acceptance.

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……………………………This dissertation is dedicated to Dr. David Jonassen, a great mentor and wonderful friend.

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ABSTRACT

This study explored the effects of alternative forms of argumentation on undergraduates' physics solutions in introductory calculus-based physics. A two-phase concurrent mixed methods design was employed to investigate relationships between undergraduates' written argumentation abilities, conceptual quality of problem solutions, as well as approaches and strategies for solving argumentative physics problems across multiple physics topics.

Participants were assigned via stratified sampling to one of three conditions (control, guided construct, or guided evaluate) based on gender and pre-test scores on a conceptual instrument. The guided construct and guided evaluate groups received tasks and prompts drawn from literature to facilitate argument construction or evaluation. Using a multiple case study design, with each condition serving as a case, interviews were conducted consisting of a think-aloud problem solving session paired with a semi-structured interview. The analysis of problem solving strategies was guided by the theoretical framework on epistemic games adapted by Tuminaro and Redish (2007).

This study provides empirical evidence that integration of written argumentation into physics problems can potentially improve the conceptual quality of solutions, expand their repertoire of problem solving strategies and show promise for addressing the gender gap in physics. The study suggests further avenues for research in this area and implications for designing and implementing argumentation tasks in introductory college physics.

CHAPTER ONE

INTRODUCTION

Physics education has been concerned with how students learn physics and how students can apply their understandings to solve physics problems (van Heuvelen, 1991). To address this concern, physics education research has predominately focused on how students gain conceptual understanding, how they organize their knowledge, and solve problems. Also physics education research has focused on how students' beliefs, attitudes, or expectations affect their learning in physics; and interconnections between the areas (Hsu, Brewe, Foster, & Harpter, 2004; Leonard, Dufrense, & Mestre, 1996). Problem solving is regarded as an integral component in undergraduate, introductory physics. It is commonly agreed that students should be able to learn and apply physics principles and concepts to solve problems (Hsu et al., 2004). Yet, many undergraduate physics students have difficulty solving problems in physics (Tuminaro & Redish, 2007).

All too often, traditional physics courses assign quantitative problems in which solutions can be obtained by identifying and manipulating equations; with the assumption that solving such problems can enhance students' understanding of physics concepts and development of problem solving skills (Leonard et al., 1996; Maloney, 1994). However, Dufrensne, Gerace, and Leonard (1997) and Leonard et al. (1996) noted that solving such problems alone does not develop a deeper understanding of physics concepts nor does it offer a means for students to develop more complex problem solving skills. Instead, having students focus on problems that use equation manipulation promotes students to approach problem solving in haphazard and ineffective ways (Reif, Larkin, & Brakett, 1976; van Heuvelen, 1991).

Physics education research (Hsu et al., 2004) reveals that students have limited problem solving abilities. They often apply formula-centered problem solving approaches such as “means-end” or “plug-and-chug” and perceive physics problem solving as memorizing, recalling, and manipulation equations (Leonard et al., 1996). Student often attend to superficial cues within the problem and apply random physical concepts without reflecting on the applicability (Chi, Feltovich, & Glaser, 1981; Mason & Singh, 2010). Too often students view science as a collection of facts and conclusions, not as consisting of problems which require evaluation of evidence or consideration of alternative solutions (Seethaler & Linn, 2004). In physics, it is common for students to only offer a numerical answer based upon their selection and manipulation of what they deem to be appropriate equations relevant to a problem at hand. They rarely offer or are encouraged to consider other alternative solutions or reflect upon the appropriateness of their answer. Also they are rarely encouraged to explain or justify why they selected and used certain equation(s) for a given problem. As Dufresne et al. (1997) describe, students typically solve problems by focusing on selecting an equation without reflecting on its appropriateness and then apply the equation to the problem information, with emphasis on obtaining a “right” answer, without attempting to understand its content. Additionally, students rarely conceptually reason about the problem, seek a novel solution to a problem, or reflect on the reasonableness of their own solution. Hence, while engaged problem solving students are often answer-oriented rather than process-oriented (Selvaratnam & Canagratna, 2008).

Numerous studies have also suggested that students’ problem solving performance can be influenced by their epistemological beliefs (Elby, 1999; Hammer, 1994; 2000; Hammer & Elby, 2002). Further, problem solving performance can also be influenced by having students solve problems in multiple representations (Finkelstein et al., 2005; Heller & Reif, 1984; Kohl & Finkelstein, 2008; Larkin, McDermott, Simon, & Simon, 1980; Meltzer, 2005; Rosengrant, Etkina, & van Heuvelen, 2006; van Heuvelen & Zou, 2001). and explicitly identifying and applying their physics understanding (Frienge & Lind, 2006; Hsu et al., 2004; Leonard et al., 1996).

After traditional physics instruction, students often come away with an incomplete understanding of physics concepts and a limited set of problem solving skills (Dufresne et al., 1997). As McDermott (1991) has advocated, solving for a correct numerical answer does not necessarily imply that a student has acquired a corresponding level of conceptual physics understanding. Not only is enhancing conceptual knowledge important, but knowing how to apply such knowledge is an important ingredient in physics problem solving (Sabella & Redish, 2007). If students are to better comprehend physics concepts, their problem solving skills need to be further refined. Yet the question still remains – what instructional innovations or alternative problem types can actually help students enhance problem solving skills?

Physics instruction often focuses on quantitative problem solving objectives that implies that students should focus on algorithmic processes opposed to applying conceptual and interpretative knowledge (Gaigher, Rogan, & Braun, 2007). Numerous instructional or curricular interventions have been developed to address students' difficulties in regards to problem solving in physics. Van Heuvelen (1991) suggest that if students are encouraged to apply more expert-like problem solving strategies, they are more likely to perform better on problem solving tasks. Common interventions include explicit instruction of problem solving heuristics (Heller & Reif, 1984), instructors modeling the use of problem solving heuristics, and encouraging students to employ heuristics when solving physics problems (Halloun & Hestenes, 1987). Also, explicitly modeling or teaching students how to use organized problem solving processes throughout the physics course can yield greater course performance than more scattered approaches (Heller & Reif, 1984; Maloney, 2011; Van Weeren, de Mul, Peters, Kramers-Pals, & Roossink, 1982; Wright & Williams, 1986). Additional strategies to improve students problem solving abilities include the use of alternative problem types (Heller & Hollabaugh, 1992; Mestre, 2002; Van Heuvelen & Maloney, 1999), conceptual approaches such as qualitative strategy writing (Leonard et al., 1996), peer reflection (Mason & Singh, 2010), cooperative group problem solving (Heller, Keith, & Anderson, 1992; Heller & Hollabaugh, 1992), and computer based tutor or homework systems (Reif & Scott, 1999). However, there are few innovative interventions or alternative problem types that emphasize qualitative analysis or both qualitative and quantitative analysis of physics problem and constructing qualitative explanations of solutions.

As alluded to above, the nature of the tasks which students engage in while solving problems can influence their learning and problem solving outcomes (Jonassen et al., 2009). As Mason and Singh suggest, "quantitative and conceptual problem solving both can enhance problem solving and reasoning skills only if students engage in effective problem solving strategies instead of treating the task purely as a mathematical chore or guess-work" (p. 748). One kind of task involves creating meaningful scientific justifications in their problem solutions. If students are to develop justifications that are more meaningful and use various types of justifications for their problem solutions, they should be engaged in meaningful problem tasks. One technique to aid in the development and use of justifications is the application of argumentation during problem solving (Jonassen et al., 2009).

Scientific argumentation requires interpretation and evaluation of evidence, assessing alternatives, and addressing counter-positions to justify a claim or solution (Driver, Newton, & Osborne, 2000). Argumentation can enhance critical thinking, decision making skills, problem solving skills, ways of thinking, encouraging conceptual change, and the process of knowledge construction and enhancement (Driver et al., 2000; Jonassen & Kim, 2010). Research also suggests that the development of argumentation skills may lead to deeper conceptual understanding. However, the relationship between argumentation and conceptual understanding is not straightforward (Dawson & Venville, 2009). Yet, it is also recognized that students have difficulty developing or evaluating arguments (Bell & Linn, 2000; Reznitskya et al., 2001; Zeidler, 1997). Specifically, students have difficulty writing persuasive essays, comprehending written arguments, generating evidence, evaluating alternative explanations, and considering courter-arguments and rebuttals to support a claim or solution (Kuhn, 1991; Means & Voss, 1996). Thus the need for critical thinking skill development underscores a reason to engage students in argumentation.

Argumentation can be divided into two skills – skill of constructing an argument and skill of evaluating arguments. Effective argumentation requires the ability to evaluate, weigh evidence and counterevidence and consider arguments, counter-arguments, and rebuttals to arrive at a solution (Jonassen et al., 2009). However, as indicated by Ge and Land (2004), students need to be prompted to construct arguments to justify their proposed solutions. There are numerous methods/scaffolds to prompt students to engage in argumentation, such methods include the application of directions and question prompts. Finding ways for appropriately scaffolding students' argumentation presently remains a focus of ongoing research.

As a means to help remedy students' difficulties with understanding or solving problems and enhancing problem-solving skills, innovative instructional strategies or problems are needed. In physics, there is limited research exploring the use and effectiveness of argumentation to enhance problem solving abilities and conceptual understandings. Additionally, there is limited research exploring how we can scaffold problems to support written argumentation in the context of physics. This study is a step toward exploring the impact of argumentation scaffolding strategies in the context of physics problem solving

Purpose of the Study and Overarching Research Question

The aim of this study was to examine the effects of alternative forms of argumentation on students' physics solutions in an introductory calculus-based physics course. Rather than asking students to solve traditional physics problems, the study used problems similar to those in *Physics by Inquiry* (PbI; McDermott, 1996) curriculum – open-ended and hypothetical pseudo debate tasks. These tasks were modified to scaffold students' construction or evaluation of arguments and compared to typical "explain your reasoning" question format. Additionally, the goal of this study was to examine how students solved these problems and what problem solving strategies they employed while solving such argumentative problem tasks. Hence, this study sought to investigate whether the integration of written argumentation into physics problems can help support students' abilities to solve problems and improve conceptual understanding of physics.

The overarching research question of this study was, what patterns of undergraduates' argumentation quality, conceptual quality of problem solutions, and problem solving strategies can emerge in introductory physics across multiple topics while solving problems supporting alternative forms of argumentation? The following sub-questions were developed to address the overarching research question from both quantitative and qualitative phases. By employing a mixed-method design, this study aimed to investigate relationships between students' argumentation abilities, quality of problem solutions, and how students' approach solving argumentation problems across multiple physics topics.

Significance of the Study

The significance of the study is four-fold. First, there has been little research in regards to argumentation in the context of physics. For instance, Nussbaum and Sinatra (2003) and Nussbuam, Sinatra, and Poliquin (2008) examined the role of argumentation in the context of physics problem solving, however the students who participated in these studies had limited physics background and were conducted in the context of a psychology classroom opposed to a physics classroom. Acar (2008) also examined the role of argumentation in the context of physics problems however; the population under investigation was pre-service science teachers. Thus the results of this study are valuable for understanding the effectiveness of incorporating argumentation in introductory physics.

Second, there have been studies in various disciplines concerning the use of prompts or forms of argumentation to promote students' argumentation skills. Yet, there has been limited research concerning how to prompt students' written arguments in the context of physics. Hence this study utilizes two alternative forms of argumentation to prompt students. These alternative forms of argumentation include construct an argument question prompts and evaluate alternative arguments question prompts. These alternative forms of argumentation are compared to responses received from the control ("What is the answer? Explain your reasoning.") condition.

Third, this research is significant because there has been limited research concerning how argumentation relates to physics students' conceptual understanding. There have been studies concerning relationships of argumentation and science learning in other science disciplines or socioscientific issues (e.g. Sadler & Fowler, 2006) but few such studies have been completed in physics.

Finally, there has been little research concerning how students approach solving argumentation problems. There has been extensive research in physics education literature concerning how students solve traditional textbook physics problems but little has examined how students approach novel problems such as problems that support argumentation. Consequently, this study employed a multiple-case study approach to examine emerging themes of how students approach solving problems with alternative forms of argumentation.

Theoretical Framework

Two areas of research guided the design, interpretation, and analysis of the study: quality of arguments and forms of epistemic games to solve problems. In the following sub-sections each of the aspects are reviewed in relation to the context of this study.

Quality of Arguments

Toulmin's argumentation pattern (TAP) (1958) is commonly used in argumentation research, to both instruct individuals about argument structure and to analyze the structure and features of an argument. Toulmin describes argumentation as a reasoning process that can occur across domains and the argument structure is context-independent but the undergirding features of an argument are context-dependent. According to Toulmin, statements that undergird an argument can be identified and classified into one of six categories: claim, data, warrants, backing, qualifiers, and rebuttals. Claims are conclusions or assertions, data are the facts that provide the foundations of the claim, warrants are the proposed reasons (e.g. rules or principles) that provides connection between data and claim or conclusion, backing are the assumptions used to provide justification of the warrant, qualifiers are the conditions or limitations under which the claim is true, and rebuttals specify the conditions when the claim is not true (Driver et al., 2000). Toulmin's (1958) framework suggests that the construction of a scientific argument is a process of using data, warrants, and backings to convince others of the validity of the proposed claim. The strength of the argument is primarily based on the presence or absence of specific combinations of these structure features (Sampson & Clark, 2008). Specifically, a stronger argument would contain all of these argument features.

There are three criteria an argument should ideally satisfy: relevance, sufficiency, and acceptability (Blair & Johnson, 1987; Jonassen, 2011). Specifically, is the premise(s) of an argument acceptable, relevant to the conclusion, and does it provide sufficient support for the conclusion (Blair & Johnson, 1987)? Generally, these three criteria can be useful in judging the effectiveness of most arguments (Jonassen & Kim, 2010). Kuhn (1991) identifies five argumentation skills: generating causal theories, offering supporting evidence, envisioning conditions that undermine one's theory, generating alternative theories, and rebutting alternative theories. Thus, successful argumentation requires a problem solver to develop and articulate a reasonable solution support the solution with data and evidence, as well as identify alternative solutions (Cho & Jonassen, 2002). The strength of an argument depends upon the context (Newton, Driver, & Osborne 1997), and the nature of the task (Sampson & Clark, 2008).

In this study, I used TAP to analyze the strength of arguments offered by participants in varying contexts. Although TAP has been used in science and non-science disciplines, it has some limitations: it focuses on the structure of an argument and not its correctness; it overlooks the context in which an argument is embedded; it raises over reliability concerns for distinguishing the components of an argument (Sampson & Clark, 2008); it fails to consider both sides of an issue (Leitao, 2001) thus minimizing the role of an opponent in the process, Finally, it is difficult to apply when assessing two or more arguments at a time (Jonassen & Kim, 2010).

Epistemic Games

Presently, many physics education researchers adopt a resource model of knowledge based on diSessa's (1993) phenomenological primitives (p-prims). The resource model describes knowledge in terms of resources for learning that are both conceptual and epistemological in nature. A resource represents a fine-grain sized cognitive element of knowledge or set of knowledge elements that can be activated to solve a problem (Hammer, 2000; Sabella & Redish, 2007). Conceptual resources include, but are not limited to, intuitive knowledge about physical phenomena and causal mechanisms (Redish & Hammer, 2009). This model explains why students might have the necessary knowledge or skills for problem solving in one context but fail to activate them in another context. The resources model suggests that instruction should be designed to encourage productive activation of students' resources in appropriate contexts.

Tuminaro and Redish (2007) extended the ideas by diSessa (1993; diSessa & Sherin, 1998), Sherin (2001), and Minstrell (1992) and by Collins and Ferguson (1993) to generate a detailed framework, situated in the resource model perspective, to analyze the cognitive processes employed by students – correctly or incorrectly – while solving physics problems. Hence, they extended the resources model to include epistemic games. Epistemic games as introduced by Collins and Ferguson (1993) are normative activities executed by experts to solve problems. Specifically, epistemic games are a complex "set of rules and strategies that guide inquiry" (as referred to in Tuminaro & Redish, 2007, p. 4). For instance, Collins and Ferguson identify a simplistic epistemic game as list making because a list implicitly builds knowledge to satisfy a goal (Tuminaro & Redish, 2007). Tuminaro and Redish extend the idea of epistemic games to include ethnographic descriptions of observed student behavior as they solve physics problems. Tuminaro and

Redish (2007) indicates that an epistemic game has two ontological components – a knowledge base and an epistemic form:

> An epistemic game is not simply a structure or a set of associated knowledge; it is a pattern of activities that can be associated with a collection of resources. The collection of resources that an individual draws on while playing a particular epistemic game constitutes the knowledge base. The epistemic form is a target structure, often an external representation that helps guide the inquiry during an epistemic game (pp. 4-5).

As indicated by Tuminaro and Redish (2007), students bring to bear a wealth of knowledge and ideas (or resources) while solving problems. In order to understand what students are doing while solving problems, one needs a description of the way their resources are organized and used while solving problems. One way to describe these behaviors is by adapting the idea of epistemic games. Tuminaro and Redish refer to an epistemic game as a coherent, goal-oriented activity that guides and limits what knowledge students' think is appropriate to apply for a given problem solving task. Tuminaro and Redish indicated that their framework provides an ontological classification of cognitive structures and a description of the relationship between cognitive structures to analyze students' application of mathematics to physics problems. As described by Tuminaro and Redish, such activities are epistemic in that students engage in them as a means to construct new knowledge. They are referred to as a game in the sense that they are a coherent activity with ontology components that identify the "things" of a game and structure to differentiate an activity from others. Specifically, structure can include beginning and ending states, moves, and rules. Similarly in the context of physics problem solving, epistemic games can have ontological components, such as concepts, principles, equations and structure, such as beginning and ending states of the game, allowed moves, rules.

Epistemic games in this sense refer to behaviors that students engage in for the purpose of creating knowledge – in this case the solution to a problem. Students may enter a game in an attempt to solve a physics problem however; their expectations about physics problems determine the entry and ending conditions. Students' categorizations of physics problems and/or preconceived notions of the nature of problem solving in physics can influence their expectations. Also, students' epistemological stances can influence which epistemic game they opt to play. For instance, if a student believes that physics problem solving requires memorization of equations, such notion can influence which epistemic game they may employ and what their physics answer should look like (Tuminaro & Redish, 2007).

By identifying these games, one can deconstruct students' expectations about how to approach problem solving in physics. Tuminaro (2004) and Tuminaro and Redish (2007) identified six epistemic games or problem solving approaches, as described below, students employed while solving open-ended and algebraic physics problems. They include: (i) mapping meaning to mathematics, (ii) mapping mathematics to meaning, (iii) physical mechanism game, (iv) pictorial analysis game, (v) recursive plug-and-chug, and (vi) transliteration to mathematics. Descriptions of each of the six epistemic games identified by Tuminaro and Redish (2007) are synthesized below.

Mapping meaning to mathematics. Mapping meaning to mathematics is considered to be one of the most intellectually complex epistemic games identified. During this game, students progress form a conceptual understanding of the physical situation elicited from the problem statement and progress toward a qualitative solution. Steps or moves during this game include: (1) developing a story about the physical situation, (2) translating quantities in the story to mathematical entities, (3) relating the mathematical entities to the physical story, (4) manipulating mathematical symbols, and (5) evaluating and interpreting the story. The set of mathematical and physics resources serve as the knowledge base for this game. However, different resources may be activated during the different moves of the game. Mathematical expressions that students generate during moves (2) and (3) serve as the epistemic form which guides the direction of the inquiry.

Mapping mathematics to meaning. Mapping mathematics to meaning is considered to be the second most intellectually complex epistemic game identified. Students must develop a conceptual story based upon a particular physics equation they had identified. The moves of this game include: (1) identifying target concepts, (2) identifying an equation relating the target concepts to other concepts, (3) telling a story using the mathematical relationship between concepts, and (4) evaluating the story. Hence the structure of this game is opposite to that of mapping meaning to mathematics. Mapping mathematics to meaning involves the same knowledge base and epistemic form as mapping meaning to mathematics. However, as Tuminaro and Redish (2007) noted, that particular resources and equations employed in each game can vary from problem to problem.

Physical mechanism game. Students who employ the physical mechanism game attempt to construct a physically coherent, descriptive story based on their intuitive sense of the physical mechanism. During this game, students do not make explicit reference to a physical principle or equation. The moves during this game include: (1) develop a story about the physical scenario and (2) evaluate the story after which students decide they are done. Resources such as reasoning primitives, intuitive mathematics knowledge, symbolic forms, and interpretive devices may serve as the knowledge base for this game, along with the previously mentioned games. Unlike the previous two epistemic games mentioned, the epistemic form of this game is a story or description of the mechanism and what is happing in terms of physical principles, not equations.

Pictorial analysis game. During the pictorial analysis game, students generate an external representation (e.g. free-body diagram or circuit diagram) that indicates the relationship between influences in the problem statement. The moves of this game include: (1) identifying the target concept, (2) deciding upon an external representation, (3) constructing a conceptual story about the physical situation based on spatial relations among the objects, and (4) filling in the slots in the representation. The resources mentioned in the above games in addition to representational translation resources serve as the knowledge base. The epistemic form is the schematic or diagram that students generate which guides their inquiry.

Recursive plug-and-chug. During recursive plug-and-chug, students apply quantities into physics equations in order to seek numerical answers without conceptually understanding the physical implications of the answer. They do not construct a conceptual story to justify the use of an equation. Students do not draw on intuitive knowledge but instead simply identify quantities from the problem statement and plug them into the equation. Here, students only identify the quantity and corresponding symbol and do not attempt to conceptually understand what the quantity represents physically as they do in the mapping meaning to mathematics or mapping mathematics to meaning epistemic games. The moves during the recursive plug-and-chug game include: (1) identifying target quantities, (2) finding an equation relating the target quantities to other quantities, (3) determining which of the other quantities are unknown, and (4) calculating the target quantity. The recursive nature of this game comes about if there are additional unknowns in the problem in which they must they choose a sub-goal and start the process over again. Resources such as intuitive mathematics knowledge, reasoning primitives, symbolic forms, and interpretive devices are usually not active during this game. Instead they rely on syntactic understanding of physics symbols. The epistemic form of this game is similar to mapping mathematics to meaning or mapping meaning to mathematics – equations.

Transliteration to mathematics. Transliteration to mathematics is a game in which students utilize worked examples to generate a solution for novel problems without acquiring a conceptual understanding of the example. Here, students map quantities form a target problem directly onto the solution pattern of an example problem. The moves in this game consists of: (1) identifying target quantities, (2) finding a similar solution pattern that relates to the current problem scenario, (3) mapping quantities in the problem scenario on the solution pattern of an example problem, and (4) evaluating the mapping. Resources associated with syntactic structure of equations serve as the knowledge base. The epistemic form of this game is the solution pattern of the target example.

Tuminaro and Redish (2007) stress that the six identified epistemic games employed during problem solving in physics consists of all possible problem-solving approaches that they observed. Additionally, they do not claim to have identified all possible moves within a game. One may postulate as to whether new games or steps may emerge while solving alternative forms of physics problems. In this study, I utilize the epistemic games theoretical framework as proposed by Tuminaro and Redish (2007) to examine what problem solving strategies students may engage in while solving alternative forms of argumentative physics problems. Further, I leave open the possibility that epistemic games additional to those described by Tuminaro and Redish may emerge as students alternative forms of argumentative physics problems.

Definition of Terms

The following terms are defined for this study:

Argumentation: Argumentation is a process of making claims and providing justifications for the claims using evidence (Cho & Jonassen, 2002; Sampson & Clark, 2008). It is a critical thinking skill used in both formal and informal contexts, occur between two people or individually with one's self, and is the means by which we logically resolve questions, make decisions, formulate ideas, and solve problems (Cho & Jonassen, 2002).

Argument: An argument is defined as "an assertion with accompanying justification" (Kuhn, 1991, p. 12). Similarly, Means and Voss (1996) describe an argument as "a conclusion supported by at least one reason" (p. 141). Hence, an argument is an artifact that is created when an individual is asked to articulate and justify their claim(s) (Sampson & Clark, 2008).

Claim: A claim is an expressed opinion, conclusion, or solution from an arguer.

Condition: A condition refers to a restricting factor or state of being. In this study, a condition refers to an assignment of a state (control, guided construct, or guided evaluate) in which an individual is restricted to and operates in while solving an argumentative physics problem.

Counter-argument: There is potential for other alternative theories to explain a phenomenon. Counter-argument is the identification of and arguing for an alternative theory that undermine the previously proposed claim (Kuhn, 1991).

Epistemic Game: According to Tuminaro and Redish (2007), epistemic game refers to a coherent activity that utilizes diverse knowledge and processes associated with the knowledge to create knowledge or solve problems.

Epistemology: Epistemology refers to the ideas about nature and justification of knowledge that individuals may hold. Students' epistemologies are often defined as their beliefs about knowledge, learning and how knowledge is justified. Presently there is ongoing debate as to whether epistemologies are dynamic and domain or context dependent or stable across contexts. Elby (2010) considers that students' epistemologies in physics can be defined as, "their views about the nature of knowledge, knowing, and learning in physics" (p. 3).

Force Motion Concept Evaluation (FMCE): FMCE (Thornton & Sokokoff, 1998) is a 47 item survey in a multiple-choice, multiple-response format and was designed for high school and university introductory physics students and is similar to the Force Concept Inventory (FCI; Hestenes et al., 1992). The FMCE address students' difficulties with multiple representations between words and graphs in kinematics.

Justification: Links that connect data to claims in arguments. Justification(s) includes both warrants and backings which are links from data to claims according to Toulmin's argumentation pattern (1958).

Physics Course: A semester long (16-week) undergraduate, introductory physics course. Topics discussed include: mechanics, fluids, waves, oscillations, and thermodynamics.

Rebuttal: Conditions under which a claim will not be true (Driver et al., 2000).

Representation: Includes words, pictures, diagrams, graphs, mathematical equations, etc. to symbolize or stands for objects, concepts, and/or processes (Meltzer, 2005; Rosengrant et al., 2006).

Scaffolding: Techniques that can help students accomplish challenging tasks in instructional contexts. Scaffolds can nurture newly emerging skills to perform complex tasks and can be modified or phased out over time until the student can complete task on their own (Puntambekar & Hubscher, 2005).

Surface Feature: Surface feature refers to a feature of a problem that individuals may use to classify the problem. A classification is said to be based on surface features if problems are categorized based on the objects present in the problem. An antonym to surface feature is deep structure. Classifications based on deep structure are problems that are categorized based on principles or concepts applicable to solving a problem (Hsu et al., 2004).

Assumptions

To address the purpose of this study, a two-phase concurrent mixed-method approach was implemented and was based on the following assumptions:

Quantitative Phase

The assumptions made in the first phase of the study are:

1. The sample group used in the study during the 2012 spring semester is a representative sample of the population for introductory calculus-based introductory physics students in the United States.
2. The physics misconceptions identified in the literature and used to design physics argumentation problems are appropriate for the classroom population utilized within this study.
3. Items adapted from literature would still address the same misconceptions as intended.
4. Scores on the FMCE (Thornton & Sokokoff, 1998) accurately reflects students' conceptual understanding in physics.
5. Students' responses to all online homework problems in a problem set will not influence how they conceptually respond to an argumentative physics problem within the same problem set having the same underlying physical concepts.

Qualitative Phase

1. It is assumed that the population selected for this phase reflects the more generalized population of the classroom.
2. It is assumed that how students solve physics argumentation problems during the interview reflects how they would solve similar problems in other settings outside the interview session.

Limitations of the Study

Based on the design of the study, limitations of the study are described as follows:

Limitations of the Quantitative Method

1. The measurement of students' understanding was limited to their scores on the FMCE and not extended to all physics topics related to work, kinetic energy, potential energy, energy conservation, momentum, and collisions.
2. This study was limited to the participating students in a particular introductory calculus-based physics course and not extended to other countries and students in other course levels or majors.
3. A conceptual understanding instrument (FMCE) was administered during the first day of the course during their recitation session. No attempt was made to control time throughout the day in which the student completed the instrument. Additionally, students were limited to the recitation meeting time to complete the instrument. Thus, the time and condition that students completed the instruments may influence the results of the study.
4. Although students were assigned to either control, guided construct, or guided evaluate conditions, their homework with the additional physics argumentation problems were administered through an online homework system. Hence this study may be limited by cross-contamination of students discussing their problems to their colleagues in other treatment or control groups. Additionally, the time allotted to students to respond to the homework and argumentative problems and condition that students completed the problems my influence the results of this study.

5. Argumentative physics problems with the same underlying physics understanding were provided within the same homework set. Thus there may be conceptual understanding or problem solving contamination as one individual solve one problem and later the other.

Limitations of the Qualitative Method

1. Researchers need to be aware that case study approaches are a descriptive method and not an explanatory method. Thus cause-and-effect relationships from results of the qualitative portion of this study cannot be drawn.
2. Participants may not be a representative population of generalized introductory calculus-based physics group.

Organization of the Dissertation

This dissertation is divided into five chapters. Chapter One provides a brief overview of research including rationale, purpose, significance, theoretical frameworks, assumptions, and limitations of the study.

Chapter Two provides a review of literature relevant to this study and the theoretical frameworks. This chapter begins by providing documented conceptual difficulties undergraduate students' possess to topics related to kinematics, Newton's laws, work, kinetic energy, potential energy, energy conservation, momentum, collisions, rotation and rolling. The chapter follows with physics students' epistemological beliefs and problem-solving abilities in physics. Next, the chapter provides a review literature related to the importance of argumentation in science instruction. The chapter then describes students' argumentation abilities in various contexts and factors mediating argumentation. Next, the chapter describes with relationships of argumentation and conceptual understanding, and how argumentation can be supported. Finally, the chapter concludes with a discussion regarding gender differences.

Chapter Three outlines the two-phase concurrent mixed-method research design and research. This chapter includes research questions and hypotheses, details of the context of the study including course structure and topics to be studied, and overall design of the study. For the section detailing the quantitative phase, I describe variables, problems sets, instruments, participants, and methods of data collection and analysis. For the section detailing the qualitative phase, I describe the participants, methods for data collection, and methods for data analysis.

Chapter Four begins with findings from the quantitative phase regarding students' conceptual understanding of problem solutions, quality of argumentation used in the problem solutions, and pre/post-conceptual understanding scores. The next section details the findings from the qualitative phase on how students' solve argumentation problems in the context of physics and what problem solving strategies they use.

Chapter Five includes a summary of the study, conclusions, assertions on cross-case analysis of how students' approach solving of argumentation problems in the context of physics, and connections to research literature. This chapter concludes with implications and recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

This chapter is organized into eight parts. The first part of this chapter examines literature on students' understanding of physics topics about kinematics, work and energy, momentum and impulse, rotation and rolling motion, and Newton's laws - gravitation. The second part reviews research on undergraduates' problem-solving abilities in physics. The third part examines the argumentation literature concerning why argumentation is important in science instruction. The fourth part of this chapter reviews strategies for assessing argumentation. The fifth part of this chapter provides a review of students' argumentation abilities and factors mediating argumentation. Next, this chapter explores the literature on the relationships of argumentation and conceptual understanding as well as how argumentation can be supported, respectively. Finally this chapter concludes with a review of gender differences.

Conceptual Difficulties in Physics

There has been extensive research on students' misconceptions or alternative conceptions on almost all topics covered in first-semester introductory physics. Much of this research was completed in the last two decades of the 20th century. McDermott and Redish (1999) provide a review of literature on physics education research including a review of misconceptions literature.

Starting in the late 1990s, researchers (e.g. Hammer, 1996; Palmer, 1997; Thornton, 1997) began to realize that while on one hand student misconceptions and conceptual difficulties were incredibly resilient to instruction, they were not necessarily robust and coherent. In other words, students' answers to physics questions were often dependent on the context of the question (Palmer, 1997) and they evolved over time (Thornton, 1997). Over time, some researchers began to challenge the very notion that students have a set of deeply held coherent, albeit incorrect conceptions about how the world works. Rather students put together ideas to construct responses to questions and the ideas or 'conceptual resources' that they bring to bear may be sensitive to the context of the situation (Hammer, 1996). Although the notion of conceptual resources gained traction in the physics education research community, in the first decade of the 21st century, researchers continued to study students' misconceptions and develop assessments to gauge students' conceptions in various topics such as momentum and energy (Singh & Rosengrant, 2003) and rotational motion (Rimoldini & Singh, 2005).

A complete overview of misconceptions research in physics is beyond the scope of this section, rather the researcher discuss below literature on misconceptions relevant to physics problems used in this dissertation.

Kinematics

Student understanding of kinematics has been investigated since the 1980s. Trowbridge and McDermott's (1980; 1981) research has shown that students often fail to distinguish between position and velocity and between velocity and acceleration. Most of these studies were completed in the context of conceptual problems asked to students. More recently, Thaden-Koch, Dufresne and Mestre (2006) have explored whether students can apply their knowledge of kinematics to gauge the realism of animated motion. In their research, students were shown various videos of the classic two-track experiment. In this experiment, two balls are rolled down two tracks that are identical in all respects, except that one track has a dip in it. Students are asked to predict which ball will reach the end first. Thaden-Koch et. al. found that most students predicted that the ball that goes along the track with the dip will speed up and then slow back down while going back up hill. Hence, they concluded that the two balls would reach the ends of their respective track at the same time. Students' prediction is consistent with the misconception that confuses position with velocity. The speeding up and slowing down in equal measure of the ball in the track with the dip resulted in the two balls having the same final velocity, but not necessarily the same final position. So the vast majority of students who predicted that the balls would reach the end at the same time were in fact confusing the sameness of velocity with the sameness of position.

In this study, the researcher adapted the two-track problem as an open-ended question for the first in-class examination in which everyone receives the same problem format to serve as an indicator of their initial argumentation quality. The context of the problem was changed to a real-world setting – a race between two skate boarders following two different skating tracks – one with a dip and one without a dip. The correct answer to this problem requires students to recognize that the skate boarder in the track with the dip speeds up, and then for the duration of while she is in the dip she is moving faster than the other skate boarder. So, even though the skate boarder who takes the track with the dip slows down back to the same speed as the other skate boarder, the one in the dip has been traveling at a higher speed while she was in the dip and therefore she reaches the finish line first.

Work and Energy

Lawson and McDermott (1987) explored student understanding of the relationship between work and kinetic energy. Even though students could identify the mathematical relationship that the work done on an object was equal to the change in its kinetic energy, they had difficulty in applying this relationship to a laboratory demonstration. The interviewers showed students a laboratory demonstration in which two dry ice pucks of different mass moved on a flat nearly frictionless glass table under the influence of a constant force exerted by a reverse vacuum cleaner. Next, they asked the students to compare the final kinetic energies of the two pucks when they reached the same finish line on the table. In their interviews with 16 undergraduate students in non-calculus based physics, Lawson and McDermott found that only about five of these students predicted that the two pucks would have equal kinetic energies. Similarly, interviews in honors calculus-based physics, they found that only 6 of 12 students predicted that the pucks would have equal kinetic energies. Rather most students in both used their raw intuition, rather than the work-energy theorem to predict that the puck that was moving faster had a greater kinetic energy.

In this study, the researcher explores this misconception using a homework problem (Problem 1). The problem asked students to compare the work done and kinetic energies of two sleds of different masses across a nearly frictionless lake that were being pushed with the same force from the same starting point to the same finish line. The goal was to pose a problem that was susceptible to the same misconception-based reasoning as the demonstration presented by Lawson and McDermott (1987). However, the researcher of this study adapted the problem used by Lawson and McDermott to a real-world context of pushing a sled across a frozen lake, rather than pushing ice pucks on frozen glass table.

Singh and Rosengrant (2003) studied students' misconceptions about energy and momentum. They developed a 25-item multiple-choice test to assess students' knowledge of these concepts. In designing this assessment, Singh and Rosegrant conducted interviews with 10 students enrolled in introductory physics. They found that although students could state the principles of conservation of energy or momentum, they had difficulty applying these principles in several of the situations probed. In some of these situations, they knew the right answer, but could not explain how the conservation principle could be used to arrive at that answer.

In this study the researcher adapted item 2 in the Energy and Momentum Conceptual Survey (EMCS) designed by Singh and Rosengrant (2003) as a homework problem (Problem2). The problem asked students to compare the speeds of two individuals going down two different, nearly frictionless slides that started from the same height, but had different curvatures. The correct answer, based on the law of conservation of energy is that the two individuals will have the same speed because they have the same kinetic energies at the bottom, which in turn follows from the fact that they had the same potential energies at the top of the slide.

Conservation of Energy

One of the important concepts in introductory physics is the law of energy conservation. Singh and Rosengrant (2003) investigated students' understanding of mechanical energy conservation in their research underpinning the development of the EMCS. In interviews with students, they found that most students could answer the questions pertaining to the law of conservation correctly, however they could not justify why their answer was correct based on the law of conservation of energy or even kinematic equations.

In this study the researcher adapted item 4 from the EMCS (Singh & Rosengrant, 2003) as an interview problem (Problem1). The problem was adapted in that rather than two stones shot from a cliff, the problem described two bullets fired from a gun. Students had to compare the final speeds of two bullets – one that was fired upward and the other fired downward. The key concept here is for students to recognize that because kinetic energy is independent of direction, the initial kinetic energies of the two bullets were equal to each other. Further, the potential energies of the two bullets were equal to each other both initially and finally, because they were fired from the same height. Therefore, based on energy conservation, the final kinetic energies and thus speeds of the two bullets would also be equal to each other.

Conservation of Momentum

One of the important concepts in first-semester introductory physics is the law of conservation of momentum. Particularly, students are expected to apply this law in the context of elastic and inelastic collisions. Singh and Rosengrant (2003) found that when students are asked to compare speeds of objects after an elastic and inelastic collision, they typically conclude that the inelastic collision results in a greater final speed. Further they fail to recognize that momentum is a vector quantity and that when an object changes direction after a collision it transfers its momentum to the other object. Other students attempt to use Newton's II Law to predict the outcome of a collision, rather than using the law of conservation of momentum.

In this study, the researcher adapted item 5 of the EMCS (Singh & Rosengrant, 2003) as a homework problem (Problem 3). The problem asked students to compare the speeds of two blocks – one steel and the other wood. The blocks were of equal mass, and each was struck with an identical bullet traveling at the same speed. The bullet embedded itself in the wooden block, but it bounced off the steel block. Students were asked to predict which of the two blocks would be moving faster after the collision. The correct answer, based on the law of conservation of momentum, is that the steel block would move faster after being struck by the bullet, because the change in momentum is larger for the bullet that bounces back from the steel block compared to the one that embeds itself into the wooden block.

While students were expected to apply law of conservation of momentum, students had to first identify the system for which the law can be applied. Singh and Rosengrant (2003) found that students had difficulty in recognizing that the law of conservation of momentum applies to both colliding objects taken together. Rather they seemed to apply the law of conservation of momentum to each object individually.

In this study the researcher adapted item 11 from the EMCS (Singh & Rosengrant, 2003) as an interview problem (Problem 2). Students were presented with a situation in which two individuals are standing on a frictionless frozen lake. One individual threw a ball at the other person to the left. Students were asked to predict the motion of each person after the ball struck the other individual. The correct answer, using the law of conservation of momentum, was that the person throwing the ball would move to the right after throwing the ball and the other person, after receiving the ball, would move to the left to conserve the total momentum of the system. When Singh and

Rosengrant (2003) posed this question to students as a pre-test question most students predicted that the person who was struck by the ball would not move. In other words, students applied the law of conservation of momentum to each person individually rather than the system as a whole.

Momentum and Impulse

The impulse-momentum theorem is a concept that is covered in first-semester introductory physics. The theorem relates the impulse during a collision i.e. the change in momentum with the force acting on the object and the time interval over which this force acts. Singh and Rosengrant (2003) found that most students were unable to apply the theorem correctly. They often neglected to apply the principle to contexts in which they have to compare two situations where the same change of momentum occurs over different time intervals. Rather than apply the theorem starting with the recognition that the change in momentum, and thus the impulse, is the same in both cases, most students used their intuition to predict which situation would have a smaller force. Then, based on that prediction, they would infer that the impulse would be smaller as well. In other words, they clearly did not attend to the important feature of the problem that is different between the two situations namely the time of the collision.

In this study, the researcher adapted item 19 from EMCS (Singh & Rosengrant, 2003) as a homework problem (Problem 4). In this problem, students were asked to predict whether it was preferable for a bike rider to collide into haystack or a concrete wall, in case the brakes of the bike had failed. Rather than refer to the difference in the time of collision, students began to refer to the notion that colliding with a harder object gave you more energy and hence force than colliding with the softer object. Thus, they appeared to be conflating the concepts of energy and force, even though the concept of energy was not relevant to the question. The correct answer in this situation is that colliding with the haystack is preferable because the time over which the momentum changes is larger and therefore the force is smaller.

Rolling Motion

The topics of rotational motion and rolling are covered in most introductory physics courses. However, there has not been significant research on student understanding of these concepts. Presently, Rimoldini and Singh (2005) have conducted the most comprehensive study on this topic. Their research encompassed concepts such as angular kinematics, moment of inertia, torque, rotation and rolling. Their research on rolling motion did not focus on specific misconceptions per se', however they showed that students had several difficulties in recognizing understanding of the phenomenon of rolling without slipping. Particularly, they noted that students were uncomfortable with relative motion concepts and therefore they could not differentiate between the velocities at different points on rolling wheel. The students were so accustom to a preferred frame of reference that when they had to consider and visualize a different reference frame they were unable to do so.

Although the research by Rimoldini and Singh (2005) investigated student difficulties with rolling motion, all of the contexts that they investigated concerned the rolling of a single wheel. In this study, the researcher adapted item 7 from the Multiple Choice Test of Rotation and Rolling Motion Concepts (Rimoldini & Singh, 2005). The original item asked students to compare the linear velocities at different points on a rolling wheel. The researcher adapted the item to create a context in which students would have to compare the linear velocities at two points on two different wheels. The two wheels of the penny-farthing bicycle have the same linear velocity because the wheels move forward together. Therefore, the points at the top of the circumference of the two wheels will have the same linear velocity. This adapted item was used as an interview problem (Problem 3).

Moment of Inertia

Understanding the difference between the linear and rotational motion of rigid bodies involves understanding the concept of moment of inertia. Students need to understand that unlike in linear motion where they could assume that all of the mass of the object was concentrated at its center of mass, in rotational motion they must be concerned with how the mass of a rigid body is distributed.

In investigating students' misconceptions about moment of inertia, Rimoldini and Singh (2005) found that most students were not sure about the concept. For instance, they did not realize that moment of inertia was related to the distribution of mass around an axis and that the other physical quantities such as rotational kinetic energies depended upon the moment of inertia. Further, in their interviews with students, Rimoldini and Singh (2005) presented students with a problem with two disks of different masses, each with a lump of putty attached to the rim. Students were asked to compare what would happen to each disk if it were released. Most students did not mention moment of inertia in their explanations. Even when prompted by the interviewer about the moment of inertia, the students remembered vaguely that the moment of inertia depended upon the mass distribution, but they did not know the relationship, rather they focused exclusively on the difference in mass affecting the motion of the disks.

In this study, the researcher adapted item 3 from Rimoldini and Singh's (2005) Multiple Choice Test of Rotation and Rolling Motion Concepts as an interview problem (Problem 4). The item asked students to compare the rotational kinetic energy of two objects – one aluminum disk and iron wheel – that had the same mass, radius and angular velocity, but clearly had a different moment of inertia due to different mass distributions. The correct solution to this question required learners to recognize that because the mass of the iron wheel was concentrated along the rim of the wheel rather than distributed evenly throughout the disk, the moment of inertia and hence the rotational kinetic energy were greater. The researcher transformed the item into a more open ended question, which still needed the interview participants to recognize that the moments of inertia and the factors influencing it. The problem presented a scenario with two disks – red and blue – that had the same radius and thickness. However, one of these was much harder to turn than the other. Participants were asked to explain whether this meant that the disk that was harder to turn was heavier, or whether there could be any other reason for it to be harder to turn. The researcher wanted to investigate if the interview participants could recognize the fact that the disks need not necessarily have had different masses, rather they could have had the equal masses, but different mass distributions i.e. different moments of inertia. The physically correct answer to this question is that in addition to the possibility that the masses are different, the other possibility was that the masses were identical, but one of the disks – the one that was harder to turn – had its mass concentrated more toward the outer periphery, compared to the disk that was easier to turn.

Newton's Laws

Newton's Laws are an important concept in first-semester introductory physics. Students' misconceptions of Newton's Law have been researched for decades. Hestenes, Wells and Swackhamer (1992) investigated students' misconception in the design of the FCI. They found that most students used what is called the "dominance principle" to compare the forces that objects exerted on each other in an interaction. As per this principle, the "more forceful" object exerted the greater force. This meant that the object that was larger, more massive, or moving faster would exert the greater force.

The dominance principle interfered with students' application of Newton's II Law. While students could recognize that a larger force exerts a larger effect, they tended to ignore the effect of mass, thus concluding that a larger force acting on larger object would produce the same effect. Item 1 on the FCI (Hestenes et al., 1992) assesses this understanding. It asked students to predict which ball – a heavy or a light one – would strike the ground first when released from the same height. This question tested whether students who tended to ignore the fact that the heavier ball, even though it experienced greater force, did not hit the ground first because it also had a larger mass and a greater inertia.

While students' difficulties with all of Newton's Laws have been researched, one of the early studies was completed by Maloney (1984) focuses exclusively on Newton's III Law which specifically states that the forces between two interacting objects are equal and opposite. In a study with over 100 students in introductory university physics, over two-thirds predicted that the forces between two interacting objects would be unequal; often resorting to the dominance principle to decide which force was greater. Three items of the FCI (Hestenes et al., 1992) and four items on the FMCE (Thornton & Sokoloff, 1998) explored student understanding of Newton's III Law in various contexts. Two of these items presented a situation in which a car was pushing a truck. They asked students to predict whether the car or the truck would exert a larger force in two different cases. In the first case, the car was pushing the truck at a steady speed. In the other case, the car was speeding up as it was pushing the truck. Yet another item explored student understanding of Newton's III Law in the context of two students, sitting in chairs and pushing each other apart, where one student did the pushing. The results on all of these items showed that a majority of students used the dominance principle to predict that the more massive object was exerting the greater force.

In this study, the researcher used a homework problem (Problem 5) to explore student understanding of Newton's Laws in the context of gravitation. The first part of the homework problem was based on Newton's III Law. Students were asked to compare the force that the Earth exerts on a satellite in orbit and the force that the satellite exerts on the Earth. The correct answer to the first part of the problem is that the two forces are equal to each other, as per Newton's III Law. The second part of the problem was based on Newton's II Law. Students were asked to explain why the force exerted by the force on the satellite does not influence the motion of the Earth. The correct answer to the second question is that even though the forces are equal, due to the excessive mass of the Earth, its change in motion is very minute.

Also in this study, the researcher used an interview problem (Problem 5) to explore student understanding of Newton's II Law by adapting item 1 on the FCI in a different context. Participants were asked to predict whether a larger asteroid would be more likely to hit the Earth. This required the participants to first recognize that the larger asteroid would experience a greater gravitational force due to its larger mass. However, it also required them to recognize that because of its larger mass, the larger asteroid would have a larger inertia and therefore the effect of the force on its motion would be unchanged.

Review of Physics Problem Solving Research

Problem solving is regarded as an important cognitive activity that occurs throughout professional and everyday contexts. Thus the problem solving skills an individual brings to bear are important in nearly all contexts (Jonassen, 2000). In physics education, problem solving is a key component in any undergraduate physics course. Many physics instructors contend that students should not just simply learn concepts but should also be able to apply them to solve a wide variety of problems (Hsu et al., 2004). Yet, many undergraduate physics students have considerable difficulty with problem solving (Tuminaro & Redish, 2007).

Researchers in numerous disciplines discuss problem differences, problem representations, and individual differences that may affect problem solving abilities (Jonassen, 2000). Accordingly, physics education researchers explore factors affecting problem solving, what students do while solving problems, and design and evaluate instructional strategies to address problem solving difficulties. This section begins by describing points of consensus in the physics education community concerning problem solving. Next, this section discusses the assumptions made by educational researchers concerning the nature of undergraduate learners regarding problem solving.

General Goals of Problem Solving in Physics

A major consensus in the physics education research community is that instructors should not merely transmit factual information and students should not simply memorize the information. Rather, students should transfer their learning to new situations, make predictions, and solve problems (Hsu et al., 2004; Reif, 1995; Reif et al., 1976; Leonard et al., 1996). However, undergraduates generally perceive physics problem solving as memorizing, recalling, and manipulating equations (Leonard et al., 1996). Students are not blank epistemological slates. Instead, drawn from their everyday experiences, they come to class with beliefs which shapes their skills and attitudes about physics and how to approach solving physics problems. Hammer (1994), advocates that students' beliefs about knowledge and learning in physics may have a significant effect on their learning and problem solving. For instance, a student who believes that in order to solve physics problem you need to memorize and apply formulas will attempt more formula-centered strategies of problem solving opposed to other means (Tuminaro & Redish, 2007). Redish (2003) describes the notion of epistemological framing in which students' perceptions influence what epistemic resources or skills are appropriate to bring to bear in a particular context or situation. Hence, students' epistemological beliefs can offer an unique interpretive lens for instructors and educational researchers to understand students' ideas and behaviors, to assess students' abilities and needs, and adapt or design new instructional plans or strategies in light of their beliefs (Hammer & Elby, 2002).

Review of Undergraduates' Problem Solving Abilities in Physics

Few undergraduates are able to solve problems with instructor desired abilities (Hsu et al., 2004). To be successful physics problem solvers, students must have the ability to translate verbal statements into mathematical relations and vice versa, a task which is difficult for many introductory physics students (Larkin, et al., 1980). To help physics undergraduates become more competent problem solvers, it can be useful to first study how individuals solve and learn how to solve problems in physics. Such studies can then guide the development of new instructional strategies or refinement of existing strategies to improve students' problem solving abilities (Hsu et al., 2004). It should be noted that much of the research involving students' problem solving abilities in physics refers to how they solve traditional textbook type problems. Predominant areas of physics problem solving research reviewed by Docktor and Mestre (2010) and Hsu et al. (2004) relevant to this study are synthesized below.

Expert – novice differences of physics problem solving. Early studies of physics problem solving tended to focus on differences between experts (e.g. a physics instructor) and novices (e.g. an introductory physics student) in order to better characterize how students approach and learn problem solving in physics (Docktor & Mestre, 2010). It should be noted that expert and novice problem solvers do not form a dichotomy, instead it is a continuum and novices can exhibit expert-like behaviors and vice versa (Hardiman, Dufresne, & Mestre, 1989).

Chi et al. (1981) have explored how experts and novices group or categorize problems based on similarities of solutions. Experts tend to group problems based on the underlying "deep structure" or physics principles used to solve the problem. Experienced problem solvers tend to first qualitatively describe problem information, develop multiple representations to guide understanding, and utilizing that information to decide upon a solution strategy prior to writing down equations (Larkin et al., 1980; van Heuvelen, 1991). Such a concept-centered strategy typically includes the appropriate physics principles, rationale for why these apply, and a strategy for applying these to the problem (Leonard et al., 1996).

Due to their vast experience in the field, experts are able to quickly and accurately solve problems that are typically used in expert-novice investigations, such as end-of-chapter problems in an introductory physics text. Their physics intuition allows them to quickly evoke tools necessary for the problem at hand (Larkin et al., 1980). However, mastery of their physics intuition is achieved over time. Each physics textbook chapter contains a number of concepts to be learned in a short period of time (Larkin et al. 1980) which presents a challenge to students in physics if they are to achieve expert-like mastery of physics concepts.

Novice students view physics problem solving as an attempt to determine the value of an unknown quantity. They tend to approach problems in haphazard and ineffective ways (Reif et al., 1976; van Heuvelen, 1991). For instance, they calculate a quantity from the problem statement without asking themselves if their calculation will get them closer to the result (Reif et al., 1976). Novice problem solvers tend to rely on surface features to solve or categorize problem solutions (Chi et al., 1981). For instance, circular motion problems must always have mv^2/R or any problem containing a springs is a "spring problem". (Leonard et al.,1996). Often, students' lack understanding of the equations or conceptual knowledge that should be applied (Hardiman et al., 1989).

Research also demonstrates that novice problem solvers tend to use means-end or formula-centered approaches with few qualitative representations – first writing down equations containing quantities desired and variables provided in the problem, followed by mathematical manipulations to obtain the desired quantity (Chi et al., 1981; van Heuvelen, 1991). Students seldom consider the underlying concepts contained within the mathematical manipulated solution (Leonard et al., 1996). Even when students know the necessary concepts for the problem, they may be unable to solve it because they lack a systematic problem solving strategy for guiding them to apply such concepts (Reif et al., 1976). At the conclusion of a traditional introductory physics course, students are often unable to identify major concepts applicable to a problem and describe a general approach to solving a problem (Hardiman, et al., 1989). Instead they try to solve the problem by finding and manipulating equations (Leonard et al., 1996).

Representations in physics problem solving. There has been considerable research exploring how individuals use external representations while solving physics problems. Such representations include: pictures, free-body diagrams, field line diagrams, graphs, equations, etc. Specifically, studies focus on what types of representations are constructed (Larkin et al., 1980), how those representations are used (Heller & Reif, 1984; van Heuvelen & Zou, 2001), and whether students' and experts' are able to translate across multiple representations (Kohl & Finkelstein, 2008; Meltzer, 2005).

Physics educators recommend the use of multiple representations to help students become more expert-like problem solvers (van Heuvelen, 1991). Yet, during problem solving, unlike experts, students often do not use significant qualitative thinking or representations (McMillan & Swadener, 1991). Kohl and Finkelstein (2008) found that students generally prefer the problem statement be represented pictorially rather than with words, graphs, or equations. However, their preference does not necessarily make them more successful in solving problems. Several studies show that students tend to provide inconsistent answers to the same physics problem presented in different representational formats, (Kohl & Finkelstein, 2008; Meltzer, 2005). Facilitating students' use of multiple representations presents its own instructional challenges and more needs to be identified regarding specific difficulties students have with various representations (Meltzer, 2005).

Use of mathematics in physics problem solving. Important quantitative relations used in physics constitute basic conceptual building blocks (e.g. concepts or principles) that explain physical phenomena (Reif et al., 1976). Students must be able to correctly interpret quantities in a mathematical relation, correctly apply the quantities to the relation, apply the relation to the appropriate situation, and handle equivalent forms of this relation in order for them to use the quantitative relation as a conceptual tool (Reif et al., 1976). Research on use of mathematics in physics generally focuses on how quantitative mathematical tools are applied in the physics problem solving. Such research includes representing physical quantities through the use of symbols within equations (Sherin, 2001; Tuminaro & Redish, 2007), use of algebra, geometry, and calculus (Cui, Rebello, & Bennett, 2006), etc. This area of research identifies common student difficulties regarding mathematical skills for physics problem solving and describes how equations are utilized differently in each context – mathematics and physics (Docktor & Mestre, 2010). Such difficulties include using and interpreting vectors (Nguyen & Meltzer, 2003), translating text into mathematical algebraic expressions (Cohen & Kanim, 2005), interpreting the appropriate conceptual meaning and relationships from equations used in physics (Tuminaro & Redish, 2007), and not applying mathematical resources students possess in a physics context (Sabella & Redish, 2007).

Students' understanding of causal relationships among variables within an equation can also have an impact on the problem solving performance along with their conceptual understanding (Hung & Jonassen, 2006). Hung and Jonassen report on two causal reasoning methods – covariational and mechanism-based approaches. As Hung and Jonassen (2006) state, "causal relationships are established by the correlation between potential cause and effect. Covariational understanding involves comparing and contrasting an even with others in order to determine the probability of the event being the cause" (p. 1603). Specifically, if one changes a causal variable in an equation, then they should predict and observe the effect of those changes on other variables in the equation. Mechanistic explanations on the other hand "link causes to effects by describing the chain of causal events" (p. 1603). Specifically, mechanistic explanations offer an explanatory description of an observable event by describing underlying mediating processes by which a specific factor produced an event (Hung & Jonassen, 2006).

Use of worked examples or case reuse. Educational researchers have explored how students use worked-out, step-by-step problem solutions or previously solved physics problems provided by the instructor or textbooks to solve new and unfamiliar problems (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Docktor & Mestre, 2010). By analyzing examples (or cases) and extrapolating lessons learned from the example, students can then apply those examples to similar target problems (Jonassen, 2006). Mapping solution patterns from an example to a target problem is influenced by recognized similarities of objects between the two problems (Jonassen, 2006). Chi et al. (1989) explored how students utilized solved example solutions in textbooks and concluded that those who had greater success at solving problems after analyzing solved examples generally referred to specific line(s) in the example to check procedural aspects of their solution. On the other hand, those who had the least success at solving problems tended to re-read the examples to search for declarative information and a solution procedure that they could copy. Such actions was coined by Ferguson-Hessler and de Jong (1990) as “deep processing” and “superficial processing” of examples respectively. Hence, if students fail to reuse an example, appropriately it is generally because they based their comparisons on surface features and not structural features (Jonassen, 2006).

To further understand what aspects of problem solutions students tend to examine while analyzing worked problem solutions, Smith, Mestre, and Ross (2010) employed eye tracking methods to study students’ gazing patterns. Their results indicate that although students do spend a large fraction of time reading text information in the provided solution, they do not recall this information effectively at a later time. Their eye gazing patterns also suggest that they tend to jump between textual information and mathematics in an attempt to integrate the two sources of information. To better design and optimize use of worked examples, Ward and Sweller (1990) suggest that such examples should direct students’ attention to important problem features thus minimizing cognitive load by separating information sources (e.g. diagrams, test, equations, etc.) (Docktor & Mestre, 2010).

Other studies concerning worked examples reveal that if students have access to correct problem solutions and a self-diagnosis rubric, they are able to better reflect and explain the nature of the mistakes in their solution compared to when they just have the instructor’s or textbook’s solution alone (Yerushalmi, Manson, Cohen, & Singh, 2008).

Also when encouraged to correct mistakes in their solution on classroom assessments, students achieved better content understanding and improved problem solving skills (Henderson & Harper, 2009). Thus classroom interventions that incorporate students' reflection of their solutions can help improve physics students' problem solving skills.

Importance of Argumentation in Learning and Problem Solving

To support students' problem solving abilities, ways of thinking, and conceptual change, prior studies have shown that embedding argumentation activities in problem solving can be a useful strategy (Jonassen & Kim, 2010). Argumentation activities can elicit scientific reasoning (Jim´enez-Aleixandre et al., 2000), improve proficiency in advancing, critiquing and justifying claims, facilitate formative assessment (Duschl & Osborne, 2002; Osborne, Erduran, & Simon, 2004), and situate knowledge production in original contexts (Abi-El-Mona & Abd-El-Khalick, 2011; Zumbal-Saul, 2005). An emphasis on argumentation is consistent with the goal of improving students' reasoning in problem solving and proficiency in advancing, critiquing and justifying claims (Kuhn & Udell, 2003). Additionally, argumentation activities affords the opportunities to learn science content, learn about scientific practices, and understand the role of language, culture and social interaction in the process of knowledge construction (Abi-El-Mona & Abd-El-Khalick, 2011).

The conceptualization of science as argument is based on linking the thinking practices of scientist with those of students (Kuhn, 1993). Nearly a decade ago, Driver et al. (2000) and Duschl and Osborne (2002) made a case for including argumentation and its role in science education. Further, Driver et al. (2000) argued that argumentation can facilitate students' problem solving and decision making skills (Dawson & Venville, 2010). Duschl and Osborne (2002) claimed that argumentation was key to learning the nature of scientific inquiry, the construction of explanations and the evaluation of evidence.

Researchers have examined the connections between scientific argumentation and epistemologies of science. Nearly two decades ago, Kuhn (1993) posited that science instruction must no longer treat science as an accumulation of assertions to be passed on, disembodied from human thinking that gave rise to them. Unfortunately, nearly a decade after that, Driver et al., (2000) observed that science was often understood as consisting of a collection of facts and having "right" answers and that scientific data leads to uncontroversial agreed upon conclusions or assertions Recently, Bricker and Bell (2009) identified argumentation as a "core epistemic practice" of science. Thus, the goal of science is not just mastery of scientific concepts but also learning how to engage in practices similar to those of, practicing scientists who engage in argumentation to construct, articulate, and refine scientific knowledge (Jonassen, 2011).

Argumentation is important in both doing science and communicating scientific claims (Jimenez-Aleixandre et al., 2000). Students must be involved in communicating and reasoning that characterizes the discourse, tools, and culture of scientific communities of practice (Abi-El-Mona & Abd-El-Khalick, 2011). In this context, identifying and assessing alternatives, weighing evidence, interpreting text, and evaluating the potential validity of scientific claims are essential components in appropriately constructing scientific arguments (Driver et al., 2000).

In summary, in order to prepare our students to become educated citizens who are better able to make informed decisions there is a growing need to educate students about how we know and why we believe in the scientific worldview. Such a shift requires a focus on argumentation, including how evidence is used in science for constructing and evaluating explanations (Osborne et al., 2004) and solving problems (Jonassen, 2011). Presently meaningful argumentation is absent from a majority of science classrooms – including college classrooms (Abi-El-Mona & Abd-El-Khalick, 2011).

General Strategies for Assessing Argumentation

Argumentation can occur as an individual activity through writing and reflecting, or as a social, group activity (Driver et al., 2000). Bricker and Bell (2008) explain that argumentation is both verbal (requiring spoken and/or written language) and social (involving two or more people). An argument with oneself is social according to Vygotsky's (1978) conceptualization of internalization of external social forms. There are three common forms of argumentation: analytic, rhetorical, and dialectical (van Emeren, Grootendorst, & Henkemans, 1996). Deciding what kind of argument to support depends upon the learning goals (Jonassen & Kim, 2010).

Kuhn (1991) identified five argumentation skills: generating causal theories, offering supporting evidence, envisioning conditions that undermine one's theory, generating alternative theories, and rebutting alternative theories. Thus, successful argumentation requires a problem solver to develop and articulate a reasonable solution, support the solution with data and evidence, as well as identify alternative solutions, and develop theories to rebuttal alternative solutions (Cho & Jonassen, 2002). The strength of an argument depends upon the context (Newton et al., 1997), the nature of the task and the assessment framework (Sampson & Clark, 2008).

There are a several ways to assess argumentation depending upon a researcher's choice of framework and perception of what counts as a scientific argument (Abi-El-Mona & Abd-El-Khalick, 2011). The most common assessment is protocol analysis using coding schema for essays and responses (Jonassen & Kim, 2010). Numerous studies have employed and adapted TAP as a coding rubric (e.g. Bell & Linn, 2000). For instance, Sadler and Fowler (2006) developed a five-point rubric to assess the number and quality of justifications based on TAP's principles. Due to TAPs limitations in distinguishing argument features, Sadler and Fowler accepted any possible supports of justification. Argumentation skills (e.g. Kuhn, 1991) are applicable to nearly all types of well- and ill-structured problems in various domains (Jonassen & Kim, 2010). Argumentation can be incorporated into problem solving assessments such that students can be encouraged to argue how and why they solved a problem (Jonassen, 2011).

Students' Argumentation Abilities

Presently, researchers have examined the types of scientific arguments students generate, the process through which they construct, critique, and evaluate arguments, and how scientific argumentation can be better supported in classrooms (e.g. Bricker & Bell, 2009; Duschl & Osborne, 2002; Jimenez-Aleixandre, 2008; Kuhn & Udell, 2005; Kuhn & Reiser, 2006; Newton et al., 1999; Osborne et al., 2004; Sandoval & Millwood, 2005; Simon, Erduran, & Osborne, 2006; Zohar & Nemet, 2002). Although skills necessary for effective argumentation have been identified by various researchers (Kuhn 1991; Blair & Johnson, 1987) criteria for what constitutes a satisfactory argument had been articulated, students' abilities to generate and evaluate arguments is not entirely clear (Jonassen, 2011).

An early study by Kuhn (1991) showed that both adolescents and young adults are poor at constructing relationships between data and claim. Hence, providing evidence in support of a claim and understanding their relationships is an important skill that is not always learned by students. Kuhn and colleagues also found that students are unlikely to construct two sided arguments, are susceptible to belief bias. They also have difficulty distinguishing evidence from explanation to support a claim. Additionally, students often do not consider counterarguments and only construct arguments for their position (Kuhn, Schaw, & Felton, 1997; Kuhn & Udell, 2003).

Studies by Reznitskya, Anderson, McNurlin, Nguyen-Jahiel, Archodidou, et al. (2001) have found that most American students lack understanding of argumentation discourse and have difficulty comprehending written arguments, writing persuasive essays, differentiating theory and evidence, and producing evidence, alternatives, counterarguments, or rebuttals. In a study of examining students' fallacious argumentation as they form scientific and social judgments, Zeidler (1997) identified a number of problems student have during argumentation, such as: selecting only evidence that supports their claim or "my-side bias," reliance on personal beliefs rather than counter evidence, overgeneralization, and making unsupported assertions. Essentially, students are more prone to support their own arguments based on their beliefs than find confirming or disconfirming evidence (Jonassen, 2011).

Additional studies such as those conducted by Bell and Linn (2000), who analyzed arguments produced by students to explain the nature of light, found that students do tend to rely on data to support their claims but frequently do not include warrants or backings. Similarly, Jim´enez-Aleixandre et al. (2000) found that students, when constructing arguments about genetics, focus on making detailed claims but do not support them with data and warrants. Findings from such research can have considerable influence on the ways educators design technology-enhanced learning environments and classroom activities to help students learn how to productively engage in argumentation (Sampson & Clark, 2008).

The question then is, how can students be better supported to achieve superior argumentation and critical thinking skills? Much research has been done concerning how students construct and evaluate arguments. In light of those results there has also been research on creating learning environments to support students in solving authentic problems, asking questions, comparing solutions and analyze and interpret data, consider alternatives, and justify choices (Jim´enez-Aleixandre et al., 2000).

Factors Mediating Argumentation

Argumentation ability is mediated by several factors, two of these factors – dispositions and epistemologies are discussed below.

Argumentative dispositions. Although educators often emphasize having students engage in argument construction and evaluation to enhance their conceptual understandings and ways of knowing, some students are reluctant to do so (Nussbaum & Bendixen, 2003). In an effort to measure individuals' argumentativeness that is, the tendency to approach or avoid arguments, Infante and Rancer (1982) developed a 20 item instrument. Although factors such as classroom culture can affect students' willingness to argue, Nussbaum and Bendixen (2003) employed Infante and Rancer's (1982) instrument and identified three individual characteristics, that affect students' dispositions toward argumentation: epistemological beliefs, need for cognition (enjoyment from engaging in effortful, complex thinking) and extraversion (assertiveness and need to maintain warm relations). Results indicated that less well-developed epistemological beliefs were related to dispositions to avoid arguments. Tendencies to engage in argumentation were related to both need for cognition and assertiveness (cognitive dispositions and personality respectively). Hence, beliefs and need for cognition appears to affect students' dispositions to engage in various types of cognitive tasks. Extroversion predicted tendencies to avoid arguments in that, low levels of assertiveness and high levels of warmth predicted argumentation avoidance. As Nussbaum and Bendixen (2003) suggests, it is not fully understood why factors such as epistemological beliefs are related to argumentation avoidance. One suggestion is that students who avoid arguments have fewer opportunities to experience cognitive conflict, and therefore do not develop more sophisticated epistemological beliefs. Thus, learning environments may require explicit attention to individual differences that affect student disposition to engage in argumentation.

Epistemology and argumentation. Epistemological beliefs have been shown to relate to problem solving (Bendixen & Schraw, 2001), conceptual change (Qian & Alvermann, 2000), conceptual understanding (Rebello, Siegel, Witzig, Freyermuth, & McClure, 2012) and other facets of learning related to argumentation (Nussbaum et al., 2008). As mentioned previously, less-sophisticated epistemologies may influence students' tendencies to avoid arguments. On the other hand, students who have a more sophisticated level of epistemological beliefs regarding scientific knowledge tends to construct more complex and integrated arguments (Bell & Linn, 2000; Songer & Linn, 1992). However, advances to enhance less sophisticated epistemological foundations have proven difficult. As Kuhn (2010) states:

> [you] cannot simply inform students that a model of science as the accumulation of certain knowledge is incorrect and convey to them the norms that govern authentic scientific practice and the key role that argumentation plays in these norms. Instead they must be engaged in the practice of these epistemologies (p. 811).

Hence, one currently recognized approach to improve epistemological beliefs is to be immersed in the practice of argumentation. Kuhn (1991) found that students with a more constructivist epistemic perspective were more likely to reason and use evidence, including alternative and disconfirming evidence, to address claims articulated by others (Nussbaum et al., 2008). Nussbaum et al. (2008) explored the relationships between epistemic beliefs and scientific argumentation using physics problems with undergraduates. Students were divided into control and treatment groups (who received information about criteria for constructing effective scientific arguments) and by level of epistemology using Kuhn, Cheney, and Weinstock (2000) epistemic beliefs assessment. Results indicate that those in the treatment group did develop better arguments using most of the criteria given and considered more alternatives. Students with less epistemological sophistication were less critical of inconsistencies and misconceptions and interacted less with their group than those with higher epistemological beliefs. The latter group also tended to more accurately solve the problems and had fewer misconceptions.

Manson and Scirca (2006) also found that students with a higher level of epistemologies generated arguments, counterarguments, and rebuttals of a higher quality than those with low levels of epistemologies. Students in their study read two controversial topics related to socio-scientific issues and then wrote an argument, counterargument, and rebuttal for each topic. Their results also indicate that epistemological beliefs were a significant predictor of all three components of argumentation skills. Hence, skills for generating valid and supported arguments are associated with higher understanding of knowledge and knowing (Manson & Scirca, 2006).

Additionally, epistemological beliefs have been linked to students' argumentation abilities while solving physics problems (Nussbaum et al., 2008). An approach utilized by Hammer and Elby (2003) to identify and help refine students' epistemological resources in learning physics was to use a writing task in which students were asked to write an argument, a counter-argument, and response to the counter-argument. In this way, those students who viewed the task as finding a right answer were also required to respond to counter-arguments (Hammer & Elby, 2003). How can one best identify and analyze what epistemic resources have been utilized by physics students? Bing and Redish (2009) demonstrated that analysis of warrants constructed for mathematical argumentation of a physics problem can shed light on the way the student has framed the situation epistemologically. This analysis can lend itself to understanding students' development of problem solving skills. Another way to encourage content-based reflection is to ask content questions that call for justification of knowledge. Such questions can include convincing a friend or making a decision. Such tasks promote metacognitive skills that otherwise students tend not to develop (May & Etkina, 2002). Also encouraging debates in science may help students activate a set of epistemological resources they may have available for arguing different points of view (Hammer, 2000).

Attending to epistemology may help us explain the variations in student learning outcomes with research-based curricula, create more effective curricula, and be better instructors (Lising & Elby, 2005).

In turn, students' epistemological views can influence how they respond to the instructional strategies (Jones & Carter, 2007). Thus attending to students' epistemologies may help researchers and educators explain variations in student outcomes and create more effective instructional strategies (Lising & Elby, 2005). An instructional strategy suggested by physics education researchers to tap students' epistemological resources is physics argumentation tasks. These tasks can include encouraging students to construct a written argument and counter-argument (Hammer & Elby, 2003), providing questions that encourage justification or convince a friend (May & Etkina, 2002), or using students' written warrants to explore epistemological framing (Bing & Redish, 2008). However, Hammer and Elby only utilized such question tasks in a specialty physics course designed to help students learn how to understand physics, not in a traditional introductory physics course setting. May and Etkina, however, proposed the use of justification questions or a convince a friend strategy in light of their research results regarding students' physics conceptual understanding and epistemologies inferred from their self-reflection written reports. Bing and Redish have limited themselves to analyzing a warrant, as defined by Toulimin's (1958) argumentation pattern not the entire constructed argument. Also Bing and Redish analyze how the student frames the problem epistemologically not the epistemological views brought to bear during solving the problem. More research in needed at the introductory and graduate level physics in regards to what epistemologies students bring to bear while engaging in such tasks, how can these tasks be better utilized or supported to refine students' epistemological stances and argumentative abilities, and causal implication among epistemologies, problem solving abilities, and argumentation abilities. Prior studies (Nussbaum et al., 2008) have already indicated that there is a link between students' epistemologies and argumentation abilities while solving physics problems. However these epistemologies were assessed as developmental beliefs using the framework proposed by Kuhn (1991). Presently there appears to be no reported studies using more fine grained epistemological assessments or causal assessment of introductory or graduate physics students' epistemologies or of students engaging in physics argumentation tasks.

Argumentation and Conceptual Understanding

It is widely known in several domains that students who are better problem solvers also have deeper conceptual understanding in the domain. Thus, improving conceptual understanding can potentially improve problem solving performance. Another reason for fostering argumentation is that it is likely to lead to deeper conceptual understanding (Osborne et al., 2004). Wiley and Voss (1999) indicate that engagement in constructing arguments can enhance students' knowledge. By engaging in argumentation practices (e.g. developing and evaluating alternatives, evaluating evidence, addressing counter positions), students are more equipped to make informed decision in the context of everyday occurring ill-structured problems (Driver, et al., 2000). However, based on prior studies, there is a debate as to how mastery of science knowledge correlated with higher argumentation quality (Sadler & Donnelly, 2006). Research (e.g. Asterhan & Schwarz, 2007; Means & Voss, 1996; Sadler & Donnelly, 2006; Sadler & Fowler, 2006; von Aufschnaiter, Erduran, Osborne, & Simon, 2008; Wiley & Voss, 1999; Zohar &

Nemet, 2002) suggests that the development of argumentation skills may influence conceptual understanding. However, research exploring the relationship between argumentation and conceptual understanding is not straightforward (Dawson & Venville, 2010).

Von Aufschnaiter et al.'s (2008) results of student discourse showed that students can only engage in argumentation of knowledge content and levels of content abstraction that are familiar to them. If other students provided additional data or warrants at a higher level of understanding or abstraction, they were unable to rebut such information at that level. However, the study also showed that lessons based on argumentation have a positive impact on students thinking as they help to elicit students' previous ideas to relatively high levels of abstraction. Their findings further suggest that the main indicator of whether or not a high quality of argument is likely to be attained is students' familiarity and understanding of the content. The major implication of this work for developing argumentation in the classroom is the need to consider the nature and extent of students' content-specific experiences and knowledge prior to asking them to engage in argumentation.

Schwartz, Neuman, Gil, and Ilya (2003) suggest that students tend to produce one-sided arguments that consist of an assertion supported by a single make-sense or vague reason. However, after participating in the intervention that consisted of several cycles of reading, discussions, and argument generation with peers, the students were able to generate arguments that were less one-sided and more compound and included reasons that were more acceptable and relevant. Sampson and Clark (2008) suggest that lack of familiarity with an issue can prevent students from producing an argument with a complex structure (because unaware of opposing viewpoints) and an acceptable justification (because they do not know enough about the topic to provide abstract reasons).

Similarly, Zohar and Nemet (2002) showed that most students are able to formulate a simple argument consisting of a claim with a single relevant justification without any formal training about what counts as a good argument in science. However, few students used correct biological knowledge as part of their justification. After explicitly teaching students about argument quality and relevant scientific content, the researchers observed an increase in both the quality of arguments (in terms of number of justifications to support the claim) and how often they used content knowledge as part of their justification. Their results suggest that students do not refer to scientific content to justify their claims unless they have an adequate conceptual understanding and opportunities to rehearse constructing of arguments (Sampson & Clark, 2008)

In light of results concerning argumentation quality of high-school students with varying levels of content understanding of genetics by Sadler and Donnelly (2006), which are unlike the results mentioned previously, they proposed the "Threshold Model of Content Knowledge Transfer." This model has been further enhanced through the examination of argumentation quality and content understanding by high-school students, non-science majors, and science majors (Sadler & Fowler, 2006). It is typically believed that the more advanced content knowledge one possesses, the higher argumentation quality one would exhibit on a given issue. According to this model however, argumentation is related to content knowledge but in a non-linear relationship yielding three theoretical thresholds (Sadler & Donnelly, 2006; Sadler & Fowler, 2006). At the first and lowest threshold are those who lack basic content knowledge thus are unable to articulate a meaningful argument. Alternatively, at the next level, as individuals (e.g. non-science majors) attain general understanding of concepts they demonstrate a jump in argumentation quality across a threshold. As individuals gain advanced content knowledge or expert-like knowledge (i.e. science majors) they advance to an even higher level of argumentation quality which is maintained across a threshold (Sadler & Donnelly, 2006; Sadler & Fowler, 2006).

Based on the studies described above, while designing tasks to promote both high-level argumentation and students' understanding of scientific concepts, it is essential to consider both the relevance of students' prior experiences and the complexity of the tasks. Future research also needs to address the content-specific nature of the elements of an argument and its relation to conceptual understanding.

Argumentation and Conceptual Change

Although it is unclear exactly how content knowledge influences argumentation, students who experience conceptual change can refine their conceptual understandings. A growing body of research indicated that the application of argumentation in learning can lead to conceptual change (Jonassen & Kim, 2010). In a study by Nussbaum and Sinatra (2003), students who answered well-structured physics problems incorrectly were later encouraged (using question prompts) to construct an argument for the scientifically correct answer. The purpose was to engage students in refuting a misconception. Results indicated that those who constructed an argument showed improved reasoning on the problems. Also when retested a year later, their reasoning remained strong. By refuting misconceptions through construction or reading arguments that conflict with their current understandings, students can repair misconceptions and such a strategy will help them solve well-structured problems (Jonassen, 2011). Similar conceptual change results have been found in the humanities discipline. For instance, instructions to write an argumentative essay on a historical topic can produce better conceptual understanding than instructions to write a narrative, summary, or explanation essays (Wiley & Voss, 1999).

Common Methods for Scaffolding Argumentation

Simply providing students scientific or controversial issues to discuss is not sufficient in to ensure the practice of argumentation (Osborne et al., 2004). Ge and Land (2003) found that students generally do not voluntarily construct arguments to justify their proposed solutions unless prompted to do so. Some researchers have advocated for the use of direct instruction on the structure and notation of argumentation to facilitate the development of an individuals' argumentation skills. Yet, such an approach has yielded mixed results in regards to whether direct instruction can improve students argumentation skills. An alternative approach to developing argumentation skills is to scaffold these skills (Cho & Jonassen, 2002).

Presently, there are numerous methods to engage and foster argumentative discourse among students. To enhance students' conceptual understanding and problem solving, these methods may be applied to classroom instruction or open-ended learning environments (Jonassen, 2011). Common methods for engaging and supporting argumentation among students include: directions, question prompts, collaborative argumentation, and graphical argumentation aids. As reviewed by Jonassen and Kim (2010), these methods are summarized below.

Directions are provided to guide argument construction and to facilitate specific forms of argumentation, particularly to produce counterarguments. Question prompts are scaffolds through asking questions. Kuhn (1991) offers specific questions to promote argumentation based on her five skills of argumentation. For example: What do you think is the cause of school failure? How would you prove that this is the cause? Collaborative argumentation can facilitate group discussions or collaborative reasoning. They have been used online via discussion boards but not face-to-face. One method to scaffold online argumentation is the use of note starters to encourage other points of view. Graphical argumentation aids can also scaffold students' argumentation by helping the learner visualize and identify argument structures to facilitate better construction of arguments. Graphical aids include graphic organizers, Vee diagrams, Belvedere graphic tool, and ConvinceMe.

Although there are numerous methods to scaffold argumentation that are of focus of much education research, this study focuses on the utilization of direction prompts embedded within physics problems.

Types of Arguments Generated from Using Directions Scaffolds

Wily and Voss (1999) have suggested that producing written arguments may help students synthesize and enhance text comprehension. But, students often do not consider counterarguments while writing argumentative texts. As Nussbuam and Kardash (2005) point out, constructing counterarguments necessitates identifying with audiences' opposing views and potential objections, requiring higher epistemological sophistication and perspective taking.

Nussbaum and Kardash (2005) studied ways of encouraging undergraduates to consider counterarguments when writing argumentative texts. Both of Nussbaum and Kardash's experiments indicated the usefulness of explicitly asking students to generate and rebut counterarguments. Additionally, their results indicate that instructions to persuade had a negative effect on the holistic quality of essays and the number of reasons supporting their counterclaims. Students believed that identifying counterarguments would make their own arguments less persuasive (my-side bias). When provided numerous arguments on both sides of an issue, students with no directions to persuade generated more counterarguments. Thus, persuasion directions should be used sparingly. However, Nussbaum (2005) did show that persuasion directions may be better when administered as online discussions. Thus it is important to consider the environment in which persuasion directions are given.

As mentioned previously, the use of scaffolds during argumentation can enhance students' argumentation skills. There is a growing body of literature of the types of scaffolds and how they can be used effectively (Jonassen & Kim, 2010). However the type of scaffold used depends on the nature of the task.

Gender Differences in Physics and Writing

Kahle and Meece (1994) have noted that on science achievement tests, males outperform females even among students with similar mathematics and science backgrounds. It is also noted that the gender gap in science becomes more pronounced in college compared to high school. Additionally, the largest gender disparity in science achievement resides in physics (Kahle & Meece, 1994). Research literature on the gender gap in introductory undergraduate physics generally report on three broad areas:

instruction; attitudes, beliefs, and prior experiences; and assessment. In physics, one response to addressing the gender gap has included alteration of the classroom environment for interactive engagement (Doctor & Heller, 2008). Prior studies have revealed that interactive engagement instruction (Hake, 1998) reduced the gender gap as measured by a conceptual learning survey (Lorenzo, Crouch, & Mazur, 2006). However, other studies regarding interactive instruction did not reveal gender difference (Pollock, Finkelstein, & Kost, 2007). Doctor and Heller (2008) attribute different interactive engagement strategies or instructor differences in implementation as having different effects on the gender gap.

Research in undergraduate physics concerning gender difference has also focused on students' attitudes, beliefs, and prior experiences. Kost, Pollock, and Finkelstein (2009) noted that males and females differ in their incoming attitudes and beliefs about physics. Additionally, males and females have significant differences in their prior understanding of mathematics and physics and that females are less likely to take high school physics compared to males (Kost et al., 2009). Other factors such as parental support and family beliefs may contribute to the gender gap (Hazari, Tai, & Sadler, 2007). Tai and Sadler (2001) have noted that these differences might explain gender gap differences by audience of the physics class.

Physics education research has also revealed that assessment type and item context can influence the gender gap. McCullough (2004) reported a persistent gender gap on several items of the FCI (Hestenes, Wells, & Swackhammer, 1992). Additionally, McCullough (2004) found that item context (stereotypical male vs. female contexts) can affect performance on a physics assessment in which gender differences declined. Doctor and Heller (2008) also found a gender gap on the FCI but not on course grades. Hence, as Lorenzo et al. (2006) articulates, diverse and frequent assessment practices can help narrow the gender gap.

Hamilton (1998) has also noted that content and format of test items can influence gender differences, especially in the physical sciences. In a literature review by Hamilton (1998) and Weaver and Raptis (2001): studies in elementary, secondary, and undergraduate classrooms have shown that males often do have a larger advantage on multiple choice items – including mathematics and science contexts. In this vein, assessment developers have included constructed response items in addition to or instead of only multiple choice items. Potential explanations as to why females may do better on constructed response items is that they tend have stronger written verbal skills (Weaver & Raptis, 2001). However, there are mixed results from prior studies in various domains regarding whether females do perform better on constructed response items (Hamilton, 1998; Weaver & Raptis, 2001). Barnett-Foster and Nagy (1995) and Traub (1992) have shown that females do perform better on constructed response items however; there is no gender difference on multiple choice vs. constructed response items when scientific calculations are involved. In terms of mode of delivery (online vs. paper) of open-ended questions concerning social issues administered to 15- to 16-year olds. Denscombe (2008) had shown that there was no significant difference between online and paper delivery; although online answers appeared to be longer. There was however, gender differences regarding length of response in which females constructed longer answers. Despite mixed results regarding gender differences on open-ended tasks, others, such as

Rivard and Straw (2000), still recommend the use of analytical writing to make the science classroom more gender inclusive.

Pedagogical strategies such as scientific argumentation include the use of writing and constructing coherent arguments. There has been limited reported gender differences in written arguments constructed (Bell & Linn, 2000). Research shows that students' argumentation skills are limited however, with scaffolds (as described above), including question prompts, argumentation skills can be supported (Cho & Jonassen, 2002). With appropriate scaffolding, Bell and Linn (2000) found females composing stronger arguments than males. These findings are consistent with prior findings in which females write more coherent essays than males (Hyde & Linn, 1988). Indeed, females often outperform males on short answer and essay items (Gipps & Murphy, 1994). However, others find no strong gender differences in argumentation (Kuhn, 1991). Overall, limited research on gender differences in argumentation at the undergraduate level warrants additional research (Nussbaum & Schraw, 2007).

Summary

Review of research in this section shows that students can have misconceptions or conceptual difficulties concerning topics under investigation for this study – kinematics, energy and energy conservation, momentum, and collisions. Additionally, research highlights the need to help enhance introductory physics students' problem solving abilities. Students generally rely on a "means-end" approach to solving problems rather than utilizing more productive strategies such as multiple representations and considerations of relevant concepts and strategies. Additionally, students' epistemological beliefs influences how they learn physics, how they solve problems, and correlates with their conceptual understandings

Argumentation can be viewed as a viable strategy to help students enhance conceptual understanding, epistemologies, and problem solving abilities. However, little research has been conducted in how argumentation can be effective in introductory physics. Additionally, little research has been conducted as to how argumentation strategies can influence students' conceptual understandings and/or epistemological beliefs in the context of introductory physics. Review of argumentation research in varying contexts reveals that students have difficulties constructing arguments if they are not properly scaffold to do so. Hence there are several common strategies to help scaffold argumentation however, deciding which scaffolds to use requires consideration of the argumentation task under investigation. Thus there is a need for research how argumentation and argumentation scaffolds can be used in the context of physics. This research project addresses this need.

A review of the literature shows that there is a persistent gender gap in science classroom performance. Physics education research has reported on three broad areas regarding the gender gap in introductory physics: instruction; attitudes, beliefs, and prior experiences; and assessment. One notable finding of physics education research has revealed that assessment type and item context can influence the gender gap. Studies outside of physics education research has also revealed that content and format of question items can influence gender differences. To address gender differences, test developers have incorporated constructed response items. However, research suggest that there are mixed results regarding whether females do perform better on constructed response items. In the area of scientific argumentation, students can be encouraged to construct written arguments. Although there have reported gender differences regarding written arguments constructed by students, there is limited research.

CHAPTER THREE

METHODOLOGY

This chapter presents the research plan, research questions and hypothesis, context of study, overall mixed-method design, methods of participant selection, data collection, and data analysis for concurrent quantitative and qualitative phases of this study.

Research Plan

The main purposes of this study was to: (a) examine undergraduate calculus-based physics students' argumentation skills and conceptual quality of solutions while solving physics problems that incorporate alternative forms of argumentation, (b) investigate the effects of varying question prompts on students' solutions, and (c) explore how students solve and the problem solving strategies used across multiple physics topics. Specifically, the goal was to compare written arguments generated by students who constructed arguments with those who evaluated arguments (similar to hypothetical student debate problems used in the PbI (McDermott, 1996) curriculum described below, and contrast each of these arguments with written arguments generated by students who were in a control group. Additionally the goal was to compare the conceptual quality of solutions and how students solve modified physics problems supporting argumentation.

Towards this aim, a two-phase concurrent mixed-methods design (Creswell & Plano Clark, 2007) was employed. The quantitative part of this study consisted of adapting a scoring rubric for argumentation quality and designing another scoring rubric for conceptual quality of students' solutions. Additionally, a concept inventory was used to assess students' prior understandings before instruction and results were used to assign participants to either control, guided construct, or guided evaluate conditions.

In the qualitative part of the study, through a multiple case study approach (Yin, 2008), the researcher conducted an in-depth analysis of undergraduate introductory calculus-based physics students' problem solving process while solving problems supporting alternative forms of argumentation in the context of physics. Specifically, this approach offered emergent themes and a cross-case analysis for emergent patterns related to how students solve and what strategies they used. In addition, this approach provided possible explanations of how physics problems incorporating argumentation could be better designed or supported to enhance students' argumentation skills, problem solving skills and conceptual understanding. Case participants were selected based upon level of conceptual understanding prior to instruction.

To gain a clearer picture of introductory physics students' argumentation skills, problems supporting alternative forms of argumentation were designed and administered in addition to homework sets across multiple topics (e.g. work and kinetic, energy conservation, momentum conservation, momentum and impulse, rotational motion, and gravitation – Newton's laws). Similar problems related to the above mentioned topics were used during the interview sessions in addition to discussing previously solved homework problems.

Research Questions and Null Hypotheses

This study was designed to investigate the overarching question: What patterns of undergraduates' argumentation quality, conceptual quality of problem solutions, and problem solving processes emerge in introductory physics across multiple topics for problems support alternative forms of argumentation? The following sub-questions were developed to address the overarching research question from both quantitative and qualitative phases.

Quantitative:

1) Is there a difference between control, guided construct, and guided evaluate conditions and/or male and female students on their argumentation quality and/or quality of problem solutions?

   H_0^1: There are no significant differences between control, guided construct, and guided evaluate conditions on their argumentation quality and/or quality of problem solutions.

   H_0^2: There are no significant differences between male and female students on their argumentation quality and/or quality of problem solutions.

2) Is there an interaction between gender, control, guided construct, and guided evaluate conditions regarding argumentation quality and/or quality of problem solutions?

   H_0^3: There is no significant interaction between gender and guided construct, guided evaluate and control conditions regarding argumentation quality and/or quality of problem solutions.

3) Is there a relationship between the quality of students' solutions to physics problems and argumentation quality for the control, guided construct, and guided evaluate conditions?

   H_0^4: There is no significant correlation between students' argumentation quality and qualities of problem solutions for the control, guided construct, and guided evaluate conditions?

4) Is there a relationship between students' pre-conceptual understanding and/or gender and quality of problem solution and/or argumentation quality?

   H_0^5: There is no significant correlation between students' pre-conceptual understanding, and/or gender and quality of problem solutions and/or argumentation quality.

Qualitative:

1) How do undergraduate introductory physics students solve physics problems supporting alternative forms of argumentation?
2) What problem solving strategies do students use to solve problems incorporating construction or evaluation of arguments in physics?
3) In what ways are students' problem solving strategies for varying argumentation problems formats similar to or differ from traditional "explain your reasoning" problem formats?
4) What patterns emerge for problem solving strategies from students who have varying levels of conceptual understandings prior to and during the argumentation treatment?

Structure of Physics Argumentation Problems

The aim of the PbI curriculum (McDermott, 1996) is to enhance students' scientific reasoning (e.g. proportional reasoning, inductive and deductive reasoning). Unlike other introductory physics texts, the construction of the PbI curriculum guides students' development of scientific reasoning skills through a series of open-ended question tasks and hypothetical student debate tasks. For instance, to facilitate students' understanding of controlling variables, discussions by hypothetical students regarding if and how mass, volume, and density affect sinking and floating are provided. Students are required to solve these hypothetical student debates through application of appropriate conceptual knowledge and reasoning skills. Although the debate tasks are not frequently used throughout the textbook, the debate tasks provide a useful context in which reasoning skills and argumentation are and can be embedded in the curriculum (McDermott, Heron, & Shaffer, 2005; McDermott & Schaffer, 2000).

In this study, word problems in a format similar to those in PbI were designed to scaffold students' construction or evaluation of arguments and compared to traditional question formats. Arguments, counter-arguments, and rebuttals were elicited from students by providing a set of question prompts. Clarification of counter-arguments and rebuttals was viewed as important because of Kuhn's (1991) work in which reasoning between alternatives with appropriate counter-arguments and rebuttals was seen as an indicator of the quality of scientific reasoning.

To examine the effects of alternative forms of argumentation on students' solutions, two types of argumentation tasks were utilized – construct an argument and evaluate alternative arguments. Problems for the construct an argument condition were designed to provide a story problem of a physical scenario in which students were prompted to take a position and construct a solution and consider possible counter-arguments and rebuttals. For the evaluate condition, argumentation exercises were constructed such that two hypothetical students were presented in the problem as problem solvers, one supported a naïve theory and the other supported a more appropriate, but incomplete scientific theory. Students solving the evaluate alternative arguments condition were asked to evaluate two alternative solutions, select a preferred solution, justify why it is the preferred solution, and consider reasons why someone else would support another solution.

The evaluate condition was utilized because the nature of the task is similar to McDermott's (1996) PbI hypothetical student debate problems. In these problems, the problem statement consists of two hypothetical students who provide alternative solutions to a given verbal problem statement. In this study, the alternative solutions presented in the problem statement were similar to that of Acar's (2008) study using the competing theories strategy (Osborne et al., 2004). Here, the researcher used one alternative solution that has a known misconception identified in literature that undergraduate students commonly have concerning the topic (work and kinetic energy, energy conservation, momentum conservation and impulse, rotational motion, and gravitation – Newton's laws) and another alternative solution that is more scientifically correct, but does not provide all possible reasons why it is the better solution.

The control condition consisted of the aforementioned construct an argument problems but with argumentation prompts removed. Instead control problems only provide an "explain your reasoning" statement, similar to most introductory physics textbooks. The only difference between each of the three conditions is the nature of the question prompts.

Question prompts were used to scaffold construct an argument, counter-argument, and rebuttal condition for problems in addition to homework sets and interviews were adapted from Jonassen et al. (2009) and Manson and Scirica (2006). Also question prompts used to scaffold evaluate alternative arguments, counter-arguments, and rebuttals for problems in addition to homework sets and interviews were adapted from a similar study conducted by Jonassen et al. (2009) for engineering ethics problems. The specific prompts for each condition are as follows:

> *Construct condition:* Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.
>
> In your argument, consider:
>
> - What evidence supports your reasons?
> - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
> - What reasons would your classmate provide to support their conclusion?
> - What would you reply to your classmate to explain that your position is right?
>
> *Evaluate condition:* Which statement, Jamie's or Jesse's, best describes the physical phenomenon? Or, do you have another argument? Explain, elaborate, and justify your preferred solution. In your solution, consider:
>
> - What evidence and reasons supports your selection?
> - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
> - How might a classmate supporting the other solution disagree with your preferred solution?
>
> *Control condition:* What is your answer? Explain your reasoning.

The control condition question prompt is similar to the question statement used in PbI for both open-ended and hypothetical student debate problems.

Context of Study

Course Structure

This study was conducted at a large, U.S. mid-western research university, in a semester-long (16 week) course offered in the physics department during the Spring 2012 semester. Participants were enrolled in an introductory calculus-based physics course (Physics 2750). The calculus-based course is taken primarily by engineering and physics majors with an enrollment of about 300 students. Students enrolled in Physics 2750 had prerequisites of Calculus I with a grade C- or better and were concurrently enrolled in

Calculus II. Course teaching and learning goals include: (a) building a strong and robust understanding of the fundamental concepts of physics and (b) developing the skills to explicitly express and use models to describe the physical world.

The course lecture meets three times a week (Mondays, Wednesdays, and Fridays) for approximately an hour. Additionally, the course includes one laboratory (150 minutes) and one recitation (50 minutes) component in which students meet once a week. Topics covered generally include mechanics, fluids, waves, oscillations, and thermodynamics. The course employed a textbook titled *University Physics* 12^{ed} (Young & Freedman, 2007) and Mastering Physics™, an online homework system. There were five one hour examinations, no comprehensive final examination, and 10 homework sets (generally, two homework sets approximately every three weeks) that are provided within the course. Homework, recitation problems, and examinations tend to emphasize more quantitative reasoning. Table 1 provides a typical course schedule and topics discussed within the course.

Overall Design of the Study

It is noted that both quantitative and qualitative methods have strengths and limitations, but the strength of one method could offset the limitation of another (Patton, 1997). Integration of quantitative and qualitative data can allow for convergence of findings and strengthen claims or explain any lack of convergence (Creswell, 2003). To address the research questions, this study used a two-phase concurrent mixed-method design for data collection consisting of a quantitative approach in phase one and a qualitative approach in phase two.

Table 1

Course Schedule and Topics Discussed

Week	Lecture Schedule
Week 1	Introduction to Physics
	Ch 1: Vectors
Week 2	Ch 2: Motion along a straight line
	Ch 3: Motion in two or three dimensions
Week 3	Ch 4: Newton's laws of motion
	Ch 5: Applying Newton's laws
Week 4	Ch 5: Applying Newton's laws
	Examination 1 (Wednesday)
	Ch 6: Work and kinetic energy
Week 5	Ch 6: Work and kinetic energy
	Ch 7: Potential energy and energy conservation
Week 6	Ch 7: Potential energy and energy conservation
	Ch 8: Momentum, impulse, and collisions
Week 7	Ch 8: Momentum, impulse, and collisions
	Examination 2 (Wednesday)
	Ch 9: Rotation of rigid bodies
Week 8	Ch 9: Rotation of rigid bodies
	Ch 10: Dynamics of rotational motion
Week 9	Ch 11: Equilibrium and elasticity
	Ch 12: Gravitation
	Ch 14: Fluids
Week 10	Ch 14: Fluids
	Examination 3 (Wednesday)
	Ch 17: Temperature and heat
Week 12	Ch 18: Thermal properties of matter
	Ch 19: First law of thermodynamics
Week 13	Ch 19: First law of thermodynamics
	Ch 20: Second law of thermodynamics
Week 14	Ch 20: Second law of thermodynamics
	Examination 4 (Wednesday)
	Ch 13: Periodic motion
Week 15	Ch 15: Mechanical waves
Week 16	Ch 16: Sound and hearing
	Examination 5 (Friday)

At the start of Spring 2012 semester, a concept inventory – FMCE (Thornton & Sokokoff, 1998) – was used. The FMCE was administered to students within the first week of the semester to be completed in their recitation session. Via stratified, random sampling students were assigned to either a guided construct, guided evaluate, or control condition based upon responses to FMCE and gender to ensure representative samples across each of the groups.

Physics problems utilizing argumentative question prompts to support argumentation were administered in addition to homework problems on Mastering Physics™ that aligned with the appropriate homework topics. Students in the control group also solved similar problems but with the argumentation prompts removed. For each homework set, students had approximately one and half weeks to complete the assigned problems. Within Mastering Physics™, textboxes were provided such that students would type in their written argument for each of the argumentative physics questions. Responses were then scored and analyzed using rubrics for conceptual quality and argumentation quality.

For the qualitative portion of the study, a multiple case study design (Yin, 2008) was employed. Yin (2008) articulates that case studies can be a part of a mixed methods study. Creswell (2007) describes case study research as:

> A qualitative approach in which the investigator explores a bounded system (a case) or multiple bounded systems (cases) over time, through detailed, in-depth data collection involving multiple data sources of information (e.g., observations, interviews, audiovisual material, and documents and reports) and reports a case based description and case based themes (p. 73).

Each guided construct, guided evaluate, and control condition represents a case. The multiple-case study approach (Yin, 2008) allowed for the investigation of participants' problem solving process for each of the treatment groups and comparisons of emergent themes. A think aloud problem solving session paired with a semi-structured interview protocol using previously solved problems was used to collect data of participants' responses regarding how and why they are solving physics argumentation problems. During the interviews, participants solved problems supporting argumentation similar to those that they previously solved in addition to their homework. Also, participants discussed how they solved previously completed argumentative homework problems. Interviews were conducted three times during the study with participants selected via stratified random sampling from each control, guided construct, and guided evaluate condition. Specifically, interviews were conducted approximately: (1) five weeks into the semester after students solved their third homework set with additional argumentation problems, (2) after students completed their second examination and homework set relevant to their third examination, and (3) after students completed their third examination.

Data collection for both quantitative and qualitative portions of the study was conducted during nine weeks of the Spring 2012 semester after the first examination in an introductory calculus-based physics course (2750). Figure 1 provides a timeline of data collection and analysis process for this study.

Quantitative Research Phase

The first phase of this study investigated students' argumentation quality and conceptual quality of problem solutions to homework problems that support alternative forms of argumentation. Using an argumentation quality and a conceptual quality rubric, students' responses were scored for analysis. Additionally, students' pre-conceptual understanding was assessed using a concept inventory (FMCE) which was used to assign participants to either guided construct, guided evaluate, or control conditions to ensure

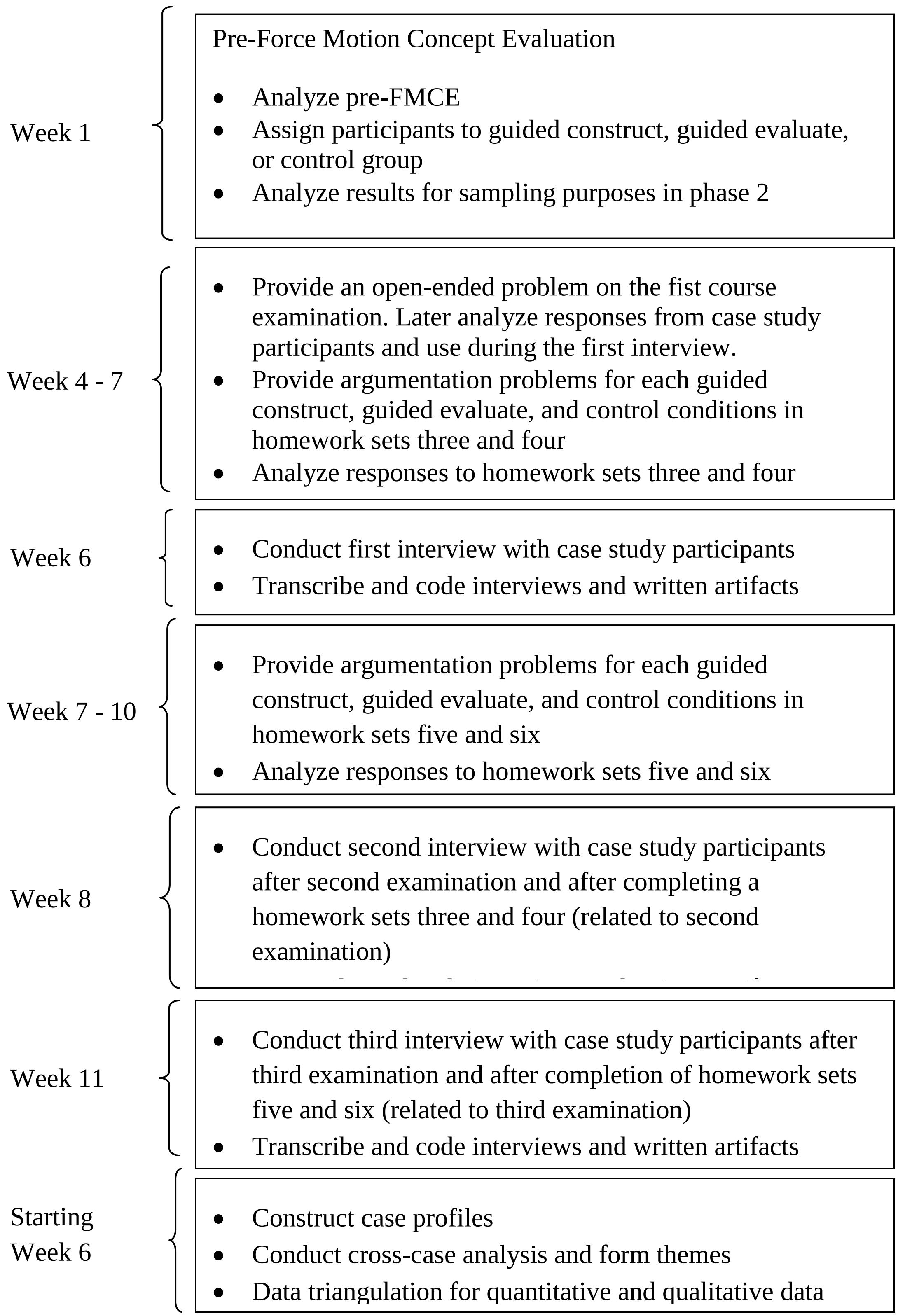

Figure 1. Timeline of data collection and analysis process for the study.

representative groups for phase one. Results from the FMCE also allowed stratified random sampling for case selection in phase two, qualitative portion of the study.

Variables. Independent variables of the study were the three conditions (guided construct, guided evaluate, and control) and gender. In a previous study by Bell and Linn (2000), it was noted that there were significant gender differences in quality of written arguments. Hence in this study gender is used as a variable to further investigate. Scores on the FMCE was also used as independent variables. Dependent variables were students' scores from rubrics used for the argumentation quality and conceptual quality of problem solutions.

Physics problem sets. Two types of alternative argumentation tasks – guided construct an argument and guided evaluate arguments – and control tasks were used in this study. Each problem task addressed a known misconception for that topic identified in physics education literature. For each homework set, the control, guided construct, and guided evaluate condition received one or two argumentation problems. The number of problems provided was limited due to course access. Table 2 describes the argumentative problems used within the homework sets. Homework sets for the control condition (addressing the topics of work and kinetic energy, energy conservation, momentum conservation, momentum and impulse, and Newton's laws) are provided in Appendix A. Similarly, homework sets for the guided construct condition are provided in Appendix B. Finally, problems for each the guided evaluate condition are provided in Appendix C.

Table 2

Description of Argumentative Problems Used in Addition to Related Homework Sets

	Topic	Misconception Addressed
Problem 1	Work and Kinetic Energy	Work done may be the same, but the kinetic energies will be different because the speeds are different (Lawson & McDermott, 1987).
Problem 2	Energy Conservation	Speeds at the bottom will depend upon the path taken. Not recognizing that the speed is related to kinetic energy which will be the same for both paths, because potential energy at the top is the same (Singh & Rosengrant, 2003).
Problem 3	Momentum Conservation in Elastic and Inelastic Collisions	Student choose the block with the embedded bullet because they believe it will move faster because the bullet transfers all of its kinetic energy to the block in the inelastic collision (Singh & Rosengrant, 2003).
Problem 4	Momentum and Impulse	Students had to realize the change in momentum is the same whether you rode your bike into a haystack or a concrete wall, but the haystack changes the momentum over a longer time and reduces your average force (Singh & Rosengrant, 2003).
Problem 5	Gravitation – Newton's III Law	That the larger object exerts a force on the smaller object, but not vice versa (Hestenes et al., 1992).

To establish content validity of the alternative argumentation tasks, problem sets were provided to three physics expert reviewers who critiqued the argumentative physics problems. Each expert reviewer had a Ph.D. in physics, had taught introductory physics, and was familiar with physics education research, particularly with undergraduate physics misconception literature. The expert reviewers noted that the argumentative physics problems do address the targeted misconceptions.

Instrumentation. To examine students' initial understandings of kinematics, Newton's laws, kinetic energy, and momentum prior to instruction the FMCE (Thornton & Sokokoff, 1998) instrument (Appendix D) was used to gather information about percentages of correct and incorrect responses and types of misconceptions. The FMCE was administered at the start of the semester in during the first course recitation session. Table 3 provides descriptive statistics of students' performance on the FMCE of the 292 students who completed the instrument.

Table 3

FMCE Descriptive Statistics

	FMCE
Minimum Score (%)	2 (0.3)
Maximum Score (%)	47 (0.7)
Mean (%)	14.71 (31.3)
Standard Deviation (%)	9.96 (21.2)
Median	11
Skewness	1.58
Kurtosis	1.77

Based upon FMCE responses (above average or below average) and gender, students were assigned to either guided construct, guided evaluate, or control condition to ensure representative samples in each condition. Three versions of argumentation problem sets – with construct an argument prompts, evaluate alternative arguments prompts, and control, "explain your reasoning" prompts were provided to the corresponding participants in a first semester calculus-based physics class.

The FMCE served three purposes:

1. Provided background information of commonalties between learners in terms of the level of understanding prior to instruction.
2. Served as a sampling technique to select participants for the phase two interviews (selection criteria is discussed in Participants section) of this study.
3. Served for data triangulation purpose. A participant's response on the diagnostic instrument provided information about their existing conceptual understanding.

Additionally, the participant's response to the problem sets provided information about their level of conceptual quality of problem solutions. The researcher was able to triangulate participant's conceptual understanding and alternative conceptions identified from the FMCE, and solutions to problem sets to the findings from written responses and discussions of previously solved problems during interview analyses and interpretation.

The FMCE (Thornton & Sokokoff, 1998) was designed for high school and university introductory physics students and is similar to the FCI (Hestenes et al., 1992), a commonly used physics content inventory. However, the FMCE covers a wider variety of topics than the FCI in particular, more questions related to kinematics and makes significant use of graphical and pictorial representations. FMCE address students' difficulties with multiple representations between words and graphs in kinematics. FMCE is a 47 item survey in a multiple-choice, multiple-response format (Redish, 2003).

The FCI was developed to gauge students' overall understanding of the Newtonian concept of force. However, questions in the FCI address conceptual understandings in limited contexts. Thus after the development of the FCI, the FMCE was developed to address each issue more thoroughly in multiple contexts (Saul, 1998). To extend the FCI, the FMCE employs a few identical items on the FCI. The remaining items were developed through student interviews and testing open-ended versions of pilot questions. Similar to the FCI, the FMCE distracters are based upon the most common responses to the open-ended versions of the questions. Validity of the FMCE was conducted by administering the instrument to hundreds of physics faculty for comparison to students' responses on the multiple-choice questions and open-ended versions. Faculty agreement was reached with interpretation and responses to all items. Additionally, there was a high correlation (>90% agreement) between students' responses to varying question formats (Saul, 1998). Pre/post-responses have also been stable and repeatable for equivalent classes at several different schools using both traditional and enhanced instruction. Results have also shown that the FCI and FMCE are comparable; with overall scores having a Pearson product coefficient correlation of 0.79 which is considered adequate for direct comparison of the two instruments' scores (Saul, 1998).

Participants. Bogdan and Biklen (2007) contend that research subjects should enter voluntarily and be informed of the nature of the study including risks and obligations involved. Thus, approval was obtained from Campus Institutional Review Board (IRB) (Appendix E). Participants in this study only consisted of those students who consented to participate as per the IRB guidelines (see Appendix F). Additionally, participants who completed *all* six additional argumentative problems within the homework sets in their respective condition provided the data. A total of 210 undergraduate responses were received at the time data analysis was conducted in this study. Table 4 provides demographics of the participant population for each condition.

Data collection. After reading students' written responses to argumentation homework problems, two scoring rubrics were constructed for analysis, one for conceptual quality of solutions (Table 5) and the other for argumentation quality of written responses (Table 6). Validation for each of the rubrics was established by: (a) providing rubrics to expert reviewers for review, and (b) two independent coders coding approximately 20% of responses. Coding consisted to two rounds of independent coding and discussions. During the first round, two independent coders coded approximately

Table 4

Demographics by Gender for Control, Guided Construct, and Guided Evaluate Conditions

		Control	Guided Construct	Guided Evaluate
Female (n = 42, 20.0%)	Above Average on FMCE	2	2	1
	Below Average on FMCE	13	11	13
Male (n = 168, 80.0%)	Above Average on FMCE	19	20	22
	Below Average on FMCE	36	37	34
	Total	70 (33.3%)	70 (33.3%)	70 (33.3%)

10% of the data with a resultant Cohen's kappa value $\kappa = 0.531$ for argumentation quality and $\kappa = 0.685$ for conceptual quality for inter-rater agreement. According to Landis and Koch (1977), $0.41 < \kappa < 0.60$ indicates "moderate agreement" and $0.61 < \kappa < 0.80$ indicates "substantial agreement". After discussing coding difference till consensus was reached, both coders again coded an additional 10% of the data. After the second round of independent coding, a resultant Cohen's kappa of $\kappa = 0.683$ for argumentation quality and $\kappa = 0.694$ for conceptual quality which is interpreted and "substantial agreement" was reached. Remaining responses were later coded by one coder.

The conceptual quality rubric is a holistic, four-point scale rubric designed to evaluate the scientific correctness students' solutions. Representative written excerpts aligning with the conceptual quality levels in the rubric and rational are presented in Appendix G.

Table 5

Conceptual Quality Rubric

Description	Points
Incorrect answer, little or no correct scientific reasoning	0
Incorrect answer, some correct scientific reasoning	1
Correct answer, little or some incorrect scientific reasoning	2
Correct answer, with correct scientific reasoning	3

Table 6

Argumentation Quality Rubric

Description	Points
No justification provided to position given	0
Justification with evidence but no grounds	1
Justification with single/multiple evidence + simple grounds.	2
Justification with single/multiple evidence + elaborated (i.e. multiple) grounds	3
Justification with single/multiple evidence + elaborated grounds and counterclaim(s)	4
Justification with single/multiple evidence + elaborated grounds, counterclaim(s) and rebuttal(s).	5

To assess argumentation quality of students' written responses a rubric adapted from Sadler and Fowler's (2006) Argumentation Quality Rubric was used in this study. The Argumentation Quality Rubric was used to determine the dominant argumentation quality theme that each participant reflects in their solution statement. Sadler and Fowler's rubric adopted Toulmin's (1958) framework to construct a five-point Argumentation Quality Rubric to help address limitations of distinguishing each argument feature. Rather than analyzing each feature of an argument, the rubric allows for analysis of how claims were justified. The rubric used in this study was adapted into a six-point rubric to allow for not just the inclusion of a counter position(s) in the justification statement but also the inclusion of a rebuttal(s) in their solutions to address counterclaim concerns. According to Sadler and Fowler, grounds refer to any of the possible supports or features (e.g. warrant, backing, qualifier) as described by Toulmin (1958). Representative written excerpts aligning with the argumentation quality levels of the rubric and rational are presented in Appendix H.

Statistical analysis of data. In order to compare the quality of written arguments and conceptual quality of solution offered by participants' responses in each of the three conditions (control, guided construct, and guided evaluate), descriptive statistics analysis and a multivariate analysis of variance (MANOVA) was performed. A MANOVA analysis was utilized because the process of data collection lead to independence between participants and the sample met the assumptions for multivariate normality. Additionally, equal sample sizes between the three conditions assured robustness to possible violations of equal covariance assumption. The three conditions (control, guided construct, and guided evaluate) and gender served as the independent variables and the conceptual quality of solutions scores, quality of argumentation scores served as the dependent variables. Univariate analysis of variance (ANOVAs) was conducted to determine if the conditions have a significant effect of each of the dependent variables (conceptual quality scores and argumentation quality scores). Partial η^2 was used to measure effect size, qualifying values $< .06$ as weak effects, values between .06 and .13 as moderate effects, and values $>.13$ as large effects (Cohen, 1988).

Subsequently, a Pearson's product moment correlation was performed for each argumentative homework problem to analyze the relationship of conceptual quality of problem solutions and argumentation quality of responses for each of the conditions. Also a multiple regression was performed for condition, FMCE scores and gender on argumentation quality scores and conceptual quality scores. An alpha level of .05 was used for all statistical tests.

Qualitative Research Phase

Merriam (2009) describes qualitative research as about understanding people's experiences and the meaning people have constructed as they make sense of their world and the experiences they have. The second phase of this study investigated how students approach solving problems supporting alternative forms of argumentation in the context of physics. Specifically, in this phase the researcher explores how and why students with varying levels of conceptual understandings approach solving argumentation problems. To this aim, the researcher employed a multiple-case study approach (Yin, 2008) in phase two in which control, guided construct, and guided evaluate conditions each constitute a case. Case studies utilize multiple data sources to construct a holistic and meaningful representation of personal experiences (Denzin & Lincoln, 2005). Also case studies are preferred when explanatory, how, or why questions are being posed (Yin, 2008). In this study, the case study approach allows for an in-depth view of students' problem solving approaches used to solve physics problems supporting alternative forms of argumentation.

Participants. Defining boundaries or units of analysis is pivotal in designing case studies (Hatch, 2002). The unit of analysis decides what it is the researcher will be able to say something about at the conclusion of the study (Patton, 2002). Thus in this study, four students from each of the control, guided construct, and guided evaluate conditions were stratified, randomly selected for the qualitative phase of this study. Each condition (control, guided construct, and guided evaluate) constituted a case for units of analysis.

Sampling was based upon level of conceptual understanding prior to instruction. Specifically, to maximize the likelihood of finding a difference between cases, participants were selected based upon an extreme conceptual understanding stance according to the FMCE. For each condition two participants were selected as having: an above average score on the FMCE and a below average score on the FMCE. Table 7 provides descriptive information about each case participant.

Creating multiple cases through stratified random sampling based on responses to the FMCE allowed the study to address the question: (a) How do undergraduate introductory calculus-based physics students approach solving physics problems supporting alternative forms of argumentation in each condition? And (b) In what ways are students' problem solving strategies for argumentation problem formats similar to or differ from traditional "explain your reasoning" problem formats? Think aloud problem solving sessions paired with a semi-structured interview protocols (Appendix I) guided each participant as they worked through problems similar to those they solved on homework sets or while discussing previously completed homework problems thereby providing a base to compare within and across cases.

Table 7

Descriptive Information About Each Case Participant

Case Condition	Gender	Ethnicity	Academic Major	Year in School	Completed High School Physics?	Score on FMCE (out of 47)
Control						
Adan	Male	Caucasian	Chemical Engineering	1st	Yes*	33
Amber	Female	Caucasian	Biological Engineering	1st	Yes	16
Alfred	Male	Caucasian	Biological Engineering	1st	Yes	13
Abby	Female	Caucasian	Electrical Engineering	1st	No	8
Guided Construct						
Blake	Male	Caucasian	Chemical Engineering	1st	Yes	40
Blaise	Male	Caucasian	Biological Engineering	1st	Yes*	32
Brice	Male	Caucasian	Chemical Engineering	1st	Yes	13
Bailey	Female	Caucasian	Mechanical Engineering	3rd	Physical Science	5
Guided Evaluate						
Cedric	Male	Caucasian	Mechanical Engineering	1st	Yes*	33
Cayden	Male	Caucasian	Computer Science	2nd	Yes	21
Carson	Male	Caucasian	Chemical Engineering	1st	No	10
Callie	Female	Caucasian	Mechanical Engineering	1st	Yes	14

Note. * = completed AP physics

Role of the researcher. Merriam (2009) states that "the researcher is the primary instrument for data collection and analysis" (p. 15). During this process, Lincoln and Guba (1985) emphasized the importance of building and maintaining trust for qualitative research. Participants need to feel comfortable to talk with the researcher to express their ideas. To create a trust relationship, the researcher contacted all the participants on a one-to-one basis to carefully explain my research goals and activities to develop trust among the participants and myself prior to the interview. Participants viewed the researcher as a graduate student in science education who wanted to study how and why they solved physics problems. Thus, they were open to the conversations with me and tried to make their thinking processes explicit to help data collection. Participants also trusted the researcher as a physics expert who would identify misconceptions or problem-solving challenges during the interview and provide feedback to them at the end of the interview as a mini-tutor session.

During the interview the researcher probed how students were solving the provided problems and why they were solving the problems as they did. Additionally, the researcher probed how they were solving the problem similar to or different from how they solved previous problems they had experienced in the physics course. The researcher's physics background, with a master's degree in physics as well as knowledge and prior experience on projects related to physics education research, allowed the researcher to identify participants' misconceptions and common problem-solving strategies.

In regards to the researcher, Merriam (2009) also states:

> The human instrument has shortcomings and bias that might have an impact on the study. Rather than eliminate these biases or "subjectivities,"

> it is important to identify them and monitor them as to how they may be shaping the study collection and interpretation of data. (p. 15)

The researcher's understanding of physics concepts and interactions with participants in the interview may have become my biases. It was not possible to be completely free of bias when probing during interview or when analyzing and interpreting data thus it was important to articulate and maintain awareness of the researcher's role. In addition to the researcher's expertise in physics, the researcher has contributed to several research projects and publications (including within the context of physics) which include qualitative and quantitative methodological design and analysis of data. Additionally the researcher has completed two qualitative research methods and three quantitative research methods (regression, analysis of variance, and multivariate analysis of variance) courses. Such expertise will contribute to the completion of this study, analysis of data, and interpretation of results.

Data collection. A semi-structured interview protocol and think aloud problem solving session (see Appendix I) was used to guide each interview session for consistency. It is assumed that individual respondents would describe the world in unique ways therefore; a less structured format allowed the researcher to respond to new emerging ideas from the respondent (Merriam, 2009). Each interview session was audio recorded for analysis. Interviews were conducted individually with each participant for each of the cases (guided construct, guided evaluate, and control) prior to and after each of the two examinations. Thus each participant completed a total of three interview sessions. Each interview lasted approximately 40 minutes. In each interview, participants were provided problems similar to their homework problems to solve. The think aloud problem solving session allowed for gathering information regarding participants' background and how and why they went about solving problems as they did. Table 8 describes the problems used in the interviews for participants to solve.

Table 8

Description of Each Argumentative Problem Used in the Interview Sessions

	Topic	Misconception Addressed
Problem 1	Energy Conservation	Speeds at the bottom will depend upon the path taken. Not recognizing that the speed is related to kinetic energy which will be the same for both paths, because potential energy at the top is the same (Singh & Rosengrant, 2003).
Problem 2	Momentum Conservation	Relationship between change in momentum and force (Singh & Rosengrant, 2003).
Problem 3	Rotational Motion	Velocity at different points on a wheel that rolls without slipping (Rimoldini & Singh, 2005).
Problem 4	Rotational Motion	Relationship between rotation and inertia (Rimoldini & Singh, 2005).
Problem 5	Gravitation – Newton's laws	That the larger object exerts a force on the smaller object, but not vice versa (Hestenes et al., 1992).

Interview problems for the control condition (addressing topics of energy conservation, momentum conservation, rotational motion, and gravitation - Newton's laws respectively) are provided in Appendix J. Similarly, homework sets for the guided construct condition are provided in Appendix K. Finally, problems for each the guided evaluate condition are provided in Appendix L.

Participants were also provided homework problems they previously completed for interview discussion. The semi-structured interview protocol allowed for the participants to reflect and the researcher to probe about the problem solving strategies used and how they had previously solved the problems. In addition to solving argumentative physics problems provided along with the homework sets, all participants completed an open-ended conceptual physics problem (see Appendix M) which the included question prompt, “What is your answer? Explain your reasoning” to address the fourth qualitative research question. The problem was administered during their first course examination and addressed a kinematics misconception identified by Thaden-Koch et al. (2006). This problem served as a baseline to assess participants’ initial argumentation quality prior to receiving the argumentative physics problems for each corresponding condition.

Data analysis. The primary data sources were audio recorded interviews and artifacts, such as written responses generated during the interview and completed homework. Participants’ responses to the FMCE served as a secondary data source. The researcher transcribed all 12 participants’ interviews verbatim and then reviewed each interview transcript for accuracy after each examination. All multi-source data were organized into a table to serve as a case record (Patton, 2002).

Yin (2008) suggests that multiple case study designs apply logic of replication in which the researcher replicates procedures for each case. Generally speaking, one should first provide a detailed description of each case and associated themes within the case followed by a thematic analysis across cases (cross-case analysis) for emerging patterns (Cresswell, 2007). The researcher applied an open coding process to each interview and written artifact with descriptive and explanatory codes and using a meaning of analysis for each of the cases. Codes were then collapsed to reduce redundancies and combined similar codes (Creswell, 2007). Themes were then developed from a refined code list for each case. Once themes emerged for a case, the researcher investigated the data closely for any refuting the emergent theme (Creswell, 2007). When case profiles were established, a cross-case analysis was performed to look for similarities and differences between the conditions (Yin, 2008). A table was constructed to compare themes across and within cases to identify emerging patterns (Creswell, 2007; Miles & Huberman, 1994). Assertions were then generated by comparing findings from each case against theoretical assertions based upon literature and comparing emerging cross-case themes (Yin, 2008).

Trustworthiness. This mixed methods design provides methodological triangulation of data to address the overarching research question (Denzin, 1978). Thus, data triangulation was addressed by including the integration of quantitative and qualitative data and the use of multiple interview questions to study how and why students solve problems supporting argumentation. Additionally, multiple data sources allowed for triangulation to increase trustworthiness of results (Janesick, 1994). In addition, to ensure the researcher used the same language and meaning of physics terminology with interview participants, the researcher regularly attended lectures to understand the instructor's approaches on teaching specific concepts. The researcher especially paid close attention to diagram, graphs, and other representations or problem solving process that may have influenced participants' ways of solving during the interview. The video-taped interviews also provided an opportunity for referential adequacy. Peer review and clarification of researcher bias were also employed as strategies to establish trustworthiness (Guba & Lincoln, 1989).

The multiple case study design employed in the qualitative portion of this study is a "common strategy for enhancing external validity or generalizability of your findings" (Merriam, 2009, p. 50). Specifically, as Miles and Huberman (1994) states:

> By looking at a range of similar and contrasting cases, we can understand a single case finding, grounding it by specifying how and where and, if

> possible, why it carries on as it does. We can strengthen the precision, the validity and stability of findings. (p. 29)

For transferability, the researcher provided a rich-thick description about context, participants' interactions and background and interactions between participant and the researcher to give a detailed description of the process as a whole. The thick description will help readers to understand how the findings are transferable to other situations (Lincoln & Guba, 1985).

Summary

This chapter presented research questions and hypotheses, the context, and to the overall-mixed method design for the study. This study utilized FMCE (Thornton & Sokokoff, 1998) to assess participants' level of conceptual understanding prior to instruction. Problems supporting alternative forms of argumentation were developed for six homework sets. Two scoring rubrics were developed and validated to assess participants' quality of argumentation and conceptual quality of problem solutions. Scores on the FMCE were used assign participants to construct, evaluate, or control conditions and to select case participants for interviews. A multiple case study approach was utilized to investigate how and why participants solve problems supporting argumentation. This analysis explored possible explanations as to how physics problems incorporating alternative forms of argumentation can be better designed to enhance students' argumentation skills, problem solving skills and conceptual understandings.

CHAPTER FOUR

FINDINGS

Introduction

This chapter is divided into two sections presenting the quantitative and qualitative findings. Findings for the quantitative phase include: descriptive statistics and tests of null hypotheses. Qualitative findings include: emergent themes of how each case solved argumentative physics problems, strategies employed by each case to solve argumentative physics problems, in what problem solving strategies vary across the cases, and emergent patterns of problem solving strategies from students how have varying levels of conceptual understanding prior to instruction and during the argumentative treatment for each case.

Quantitative Phase

Descriptive Statistics

Five problems supporting alternative forms of argumentation were administered to each respective condition (control, guided construct, and guided evaluate) via an online homework system. Participants who consented and completed all five problems in their respective condition provided the data. A total of 210 (168 male and 42 female) participants were divided between the three conditions (see Table 4).

Participants from all conditions demonstrated variability in conceptual and argumentation quality in response to the five problems administered. The distributions of scores vary across problems and gender for each problem. Means and standard deviations of conceptual and argumentation quality scores by gender for each problem are shown in Table 9.

Table 9

Means and Standard Deviations of Argumentation and Conceptual Quality Scores in Each Condition

Conditions	Control			Guided Construct			Guided Evaluate		
	Mean ± SD			Mean ± SD			Mean ± SD		
	Male	Female	Total	Male	Female	Total	Male	Female	Total
Argumentation Quality									
Problem 1	1.96 ± .72	2.27 ± .59	2.03 ± .70	3.37 ± 1.4	4.61 ± .96	3.60 ± 1.4	3.41 ± 1.4	3.57 ± 1.4	3.44 ± 1.4
Problem 2	1.78 ± .74	2.20 ± .86	1.87 ± .78	3.10 ± 1.5	4.00 ± 1.6	3.27 ± 1.5	3.39 ± 1.2	3.36 ± 1.1	3.39 ± 1.2
Problem 3	1.89 ± .67	2.40 ± .63	2.00 ± .70	2.82 ± 1.4	3.46 ± 1.3	2.94 ± 1.4	3.05 ± 1.5	3.29 ± 1.4	3.10 ± 1.5
Problem 4	1.84 ± .69	2.47 ± .52	1.97 ± .70	2.82 ± 1.4	3.00 ± 1.4	2.86 ± 1.4	3.09 ± 1.3	3.71 ± 1.2	3.21 ± 1.3
Problem 5	1.60 ± .76	1.60 ± .63	1.60 ± .73	2.79 ± 1.4	3.15 ± 1.5	2.86 ± 1.4	2.55 ± 1.5	3.29 ± 1.8	2.70 ± 1.6
Conceptual Quality									
Problem 1	1.82 ± 1.1	2.20 ± 1.1	1.90 ± 1.1	2.09 ± .83	2.46 ± .52	2.16 ± .79	2.16 ± .83	2.86 ± .36	2.30 ± .80
Problem 2	1.67 ± 1.1	2.20 ± .56	1.79 ± 1.0	2.12 ± .82	2.31 ± .75	2.16 ± .81	2.16 ± .85	2.14 ± .66	2.16 ± .81
Problem 3	1.85 ± .70	2.07 ± .88	1.90 ± .74	2.19 ± .74	2.00 ± 1.1	2.16 ± .81	2.16 ± .73	1.86 ± .66	2.10 ± .72
Problem 4	1.40 ± 1.1	2.20 ± .94	1.57 ± 1.1	1.40 ± 1.1	1.15 ± 1.3	1.36 ± 1.1	1.98 ± 1.0	2.14 ± .95	2.01 ± 1.0
Problem 5	1.45 ± 1.1	1.33 ± .98	1.43 ± 1.1	1.39 ± 1.0	1.54 ± 1.2	1.41 ± 1.1	1.45 ± 1.1	1.93 ± .83	1.54 ± 1.1

Note. Problem 1 – work and energy; Problem 2 – energy conservation; Problem 3 – conservation of momentum; Problem 4 – force and impulse; Problem 5 – gravitation (Newton’s III Law)

As can be seen in Table 9, guided construct and guided evaluate compared to control yielded higher means for conceptual and argumentation quality. Additionally, female participants tended to yield higher argumentation and conceptual quality mean scores compared to male participants for each condition across the five problems.

Tests of Hypotheses

Condition Differences and Interactions

The first null hypothesis tested for differences between conditions on argumentation quality and conceptual quality across multiple problem topics. Additionally, the second null hypothesis tested for differences between gender on argumentation quality and conceptual quality across multiple problem topics. Finally, the third null hypothesis tested for interaction between gender and condition regarding argumentation quality and conceptual quality.

The MANOVA analysis using conditions (guided construct, guided evaluate, and control) and gender as independent variables and conceptual quality scores and argumentation quality scores as the dependent variables revealed a statistically significant difference among the three conditions [Wilks' $\Lambda = 0.640$, $F(20.0, 390.0) = 4.875$, $p < .001$, $\eta^2 = 0.200$] and gender [Wilks' $\Lambda = .907$, $F(10.0, 195.0) = 2.010$, $p = .034$, $\eta^2 = 0.093$] for the five problems. However, there was no significant interaction of gender and condition [Wilks' $\Lambda = 0.864$, $F(20.0, 390.0) = 1.484$, $p = .083$, $\eta^2 = .071$] (Table 10).

These results indicate that there were significant differences between conditions for argumentation and conceptual quality scores. Additionally, there were differences between gender for argumentation and conceptual quality scores. Yet, there was no significant interaction between gender and condition regarding argumentation and conceptual quality scores. Therefore, the first and second null hypotheses were rejected and the third null hypothesis was not rejected.

Table 10

MANOVA Results for Differences between Condition and Gender and Interaction between Condition and Gender Regarding Conceptual and Argumentation Quality

Variable	F	df	*p*	Effect Size
Condition	4.88	20, 390	.000	.200
Gender	2.01	10, 195	.034	.093
Condition × Gender	1.48	20, 390	.083	.071

To detect the significance of condition and gender on each of the dependent variables, follow-up Univarinate ANOVAs were performed (see Tables 11 and 12). Univariate ANOVAs reveal significant differences with large effects among the three conditions on their argumentation scores for the five problems ($F(2, 204) = 30.32$, $p < .001$; $F(2, 204) = 23.05$, $p < .001$; $F(2, 204) = 10.10$, $p < .001$; $F(2, 204) = 12.91$, $p < .001$; $F(2, 204) = 16.02$, $p < .001$ respectively). Effect sizes (partial η^2) range from 0.090 to 0.229 respectively. Also there were significant differences with small effects on conceptual scores for Problem 1 ($F(2, 204) = 3.63$, $p = .028$) and Problem 4 ($F(2, 204) = 5.93$, $p = .003$). Effect sizes (partial η^2) are 0.034 and 0.055 for Problems 1 and 4 respectively.

Univariate ANOVAs also reveal significant differences with small effects between gender, with females outperforming males on their argumentation scores for Problems 1, 2, 3, and 4 ($F(1, 204) = 7.71$, $p = .006$; $F(1, 204) = 4.19$, $p = .042$; $F(1, 204) = 4.56$, $p = .034$; $F(1, 204) = 5.381$, $p = .021$ respectively). Effects (partial η^2) range from 0.020 to 0.036. Also there were significant differences with small effect (partial η^2 =

.036), with females outperforming males on conceptual scores for Problem 1 (F(1, 204) = 9.91, *p* = .002).

Table 11

ANOVA Results for Condition, Gender, and Interaction of Condition and Gender on Argumentation Quality

Variable		F	df	*p*	Effect Size
Condition					
	Problem 1	30.324	2, 204	.000	.229
	Problem 2	23.051	2, 204	.000	.184
	Problem 3	10.100	2, 204	.000	.090
	Problem 4	12.912	2, 204	.000	.112
	Problem 5	16.022	2, 204	.000	.136
Gender					
	Problem 1	7.713	1, 204	.006	.036
	Problem 2	4.189	1, 204	.042	.020
	Problem 3	4.564	1, 204	.034	.022
	Problem 4	5.381	1, 204	.021	.026
	Problem 5	2.589	1, 204	.109	.013
Condition × Gender					
	Problem 1	2.675	2, 204	.071	.026
	Problem 2	1.625	2, 204	.199	.016
	Problem 3	.304	2, 204	.738	.003
	Problem 4	.523	2, 204	.593	.005
	Problem 5	.890	2, 204	.412	.009

Note. Problem 1 – work and energy; Problem 2 – energy conservation; Problem 3 – conservation of momentum; Problem 4 – force and impulse; Problem 5 – gravitation (Newton's III Law)

Table 12

ANOVA Results for Condition, Gender, and Interaction of Condition and Gender on Conceptual Quality

Variable		F	df	*p*	Effect Size
Condition					
	Problem 1	3.630	2, 204	.028	.034
	Problem 2	1.249	2, 204	.289	.012
	Problem 3	.363	2, 204	.696	.004
	Problem 4	5.923	2, 204	.003	.055
	Problem 5	.894	2, 204	.411	.009
Gender					
	Problem 1	9.907	1, 204	.002	.046
	Problem 2	2.307	1, 204	.130	.011
	Problem 3	.521	1, 204	.471	.003
	Problem 4	1.615	1, 204	.205	.008
	Problem 5	.819	1, 204	.367	.004
Condition × Gender					
	Problem 1	.478	2, 204	.621	.005
	Problem 2	1.124	2, 204	.327	.011
	Problem 3	1.469	2, 204	.232	.014
	Problem 4	2.702	2, 204	.069	.026
	Problem 5	.873	2, 204	.419	.008

Note. Problem 1 – work and energy; Problem 2 – energy conservation; Problem 3 – conservation of momentum; Problem 4 – force and impulse; Problem 5 – gravitation (Newton's III Law)

To examine which conditions contribute to the significance for the dependent variables, pair-wise comparisons were performed (Tables 13 and 14). A follow-up Tukey's HSD analysis with an overall alpha level of .05 revealed that the argumentation scores for the guided construct ($M_{Problem\ 1} = 3.60$, $p < .001$; $M_{Problem\ 2} = 3.27$, $p < .001$; $M_{Problem\ 3} = 2.94$, $p < .001$; $M_{Problem\ 4} = 2.86$, $p < .001$; $M_{Problem\ 5} = 2.85$, $p < .001$) and guided evaluate ($M_{Problem\ 1} = 3.44$, $p < .001$; $M_{Problem\ 2} = 3.39$, $p < .001$; $M_{Problem\ 3} = 3.10$, $p < .001$; $M_{Problem}\ 4 = 3.21$, $p < .001$; $M_{Problem\ 5} = 2.70$, $p < .001$) conditions were statistically greater than the control ($M_{Problem\ 1} = 2.03$; $M_{Problem\ 2} = 1.87$; $M_{Problem\ 3} = 2.00$; $M_{Problem\ 4} = 1.97$; $M_{Problem\ 5} = 1.60$) condition for each of the five problems, respectively.

Yet, there were no significant differences between guided construct ($M_{Problem\ 1}$ = 3.60; $M_{Problem\ 2}$= 3.27; $M_{Problem\ 3}$ = 2.94; $M_{Problem\ 4}$ = 2.86; $M_{Problem\ 5}$ = 2.85) and guided evaluate ($M_{Problem\ 1}$ = 3.44, *p* = .714; $M_{Problem\ 2}$ = 3.39, *p* = .841; $M_{Problem\ 3}$ = 3.10, *p* = .736; $M_{Problem\ 4}$ = 3.21, *p* = .180; $M_{Problem\ 5}$ = 2.70, *p* = .760) argumentation scores for each of the five problems, respectively. Hence, results for argumentation quality reveal that the guided construct and guided evaluate conditions with prompts yield a higher argumentation quality score than the control condition.

Post hoc results also show that conceptual quality scores on the guided evaluate (M = 2.30; M = 2.16; M = 2.01) condition were statistically greater than those in the control (M = 1.90, *p* = .023; M = 1.79, *p* = .036; M = 1.57, *p* = .042) condition for Problems 1, 2, and 4, respectively. Additionally for Problem 2, the guided construct (M = 2.31) condition yielded a statistically higher score compared to the control (M = 1.79, *p* = .036) condition. Yet, there were no significant differences between guided construct (M = 2.16 and M = 1.36) and control (M = 1.90, *p* = .240 and M = 1.57, *p* = .214) for Problems 1 and 4. Also there were no significant differences between guided construct (M = 2.16 and M = 2.16) and guided evaluate (M = 2.30, *p* = .610 and M = 2.16, *p* = 1.00) conditions for Problems 1 and 2. However, for Problem 4, the guided evaluate (M = 2.01) condition yielded a statistically greater score than the guided construct (M = 1.36, *p* = .001) condition. There were no significant differences between conditions for Problems 3 and 5. Thus for the guided construct and in particular the guided evaluate conditions with prompts, participants have a higher conceptual quality in their problems solutions. These results seem to suggest that differences in problem format may be influenced by problem context/topic.

Table 13

Tukey's Follow-up HSD Analysis for Argumentation Quality

Dependent Variable	(I) Condition	(J) Condition	Mean Difference (I-J)	*p*
Problem 1	Control	Construct	-1.571	.000
		Evaluate	-1.414	.000
	Construct	Control	1.571	.000
		Evaluate	0.157	.714
	Evaluate	Control	1.414	.000
		Construct	-0.157	.714
Problem 2	Control	Construct	-1.400	.000
		Evaluate	-1.514	.000
	Construct	Control	1.400	.000
		Evaluate	-0.114	.841
	Evaluate	Control	1.514	.000
		Construct	0.114	.841
Problem 3	Control	Construct	-0.943	.000
		Evaluate	-1.100	.000
	Construct	Control	0.943	.000
		Evaluate	-0.157	.736
	Evaluate	Control	1.100	.000
		Construct	0.157	.736
Problem 4	Control	Construct	-0.886	.000
		Evaluate	-1.243	.000
	Construct	Control	0.886	.000
		Evaluate	-0.357	.180
	Evaluate	Control	1.243	.000
		Construct	0.357	.180
Problem 5	Control	Construct	-1.257	.000
		Evaluate	-1.100	.000
	Construct	Control	1.257	.000
		Evaluate	0.157	.760
	Evaluate	Control	1.100	.000
		Construct	-0.157	.760

Note. Problem 1 –Work and energy; Problem 2 – Law of conservation of energy; Problem 3 – Law of conservation of linear momentum; Problem 4 – Force and impulse; Problem 5 – Gravitation and Newton's III Law

Table 14

Tukey's Follow-up HSD Analysis for Conceptual Quality

Dependent Variable	(I) Condition	(J) Condition	Mean Difference (I-J)	*p*
Problem 1	Control	Construct	-0.257	.204
		Evaluate	-0.400	.023
	Construct	Control	0.257	.204
		Evaluate	-0.143	.610
	Evaluate	Control	0.400	.203
		Construct	0.143	.610
Problem 2	Control	Construct	-0.371	.036
		Evaluate	-0.371	.036
	Construct	Control	0.371	.036
		Evaluate	0.000	1.00
	Evaluate	Control	0.371	.036
		Construct	0.000	1.00
Problem 3	Control	Construct	-0.257	.115
		Evaluate	-0.200	.267
	Construct	Control	0.257	.115
		Evaluate	0.057	.897
	Evaluate	Control	0.200	.267
		Construct	-0.057	.897
Problem 4	Control	Construct	0.214	.470
		Evaluate	-0.443	.042
	Construct	Control	-0.214	.470
		Evaluate	-0.657	.001
	Evaluate	Control	0.443	.042
		Construct	0.657	.001
Problem 5	Control	Construct	0.014	.997
		Evaluate	-0.114	.811
	Construct	Control	-0.014	.997
		Evaluate	-0.129	.767
	Evaluate	Control	0.114	.811
		Construct	0.129	.767

Note. Problem 1 –Work and energy; Problem 2 – Law of conservation of energy; Problem 3 – Law of conservation of linear momentum; Problem 4 – Force and impulse; Problem 5 – Gravitation and Newton's III Law

Relationship between Argumentation Quality and Conceptual Quality

The fourth null hypothesis was developed to test for correlations between argumentation quality and conceptual quality of participants' written responses for each of the five problems of each condition. A Pearson product moment correlation was used to determine strength of associations between argumentation quality and conceptual quality scores (Table 15). Results indicate there were small to moderate, positive correlations, which was statistically significant, particularly for Problems 4 (r = .599, p < .001; r = .263, p = .028; r = .414, p < .001) and 5 (r = .464, p < .001; r = .273, p = .022; r = .306, p = .010) across each control, guided construct, and guided evaluate condition, respectively. There was also a significant correlation for Problem 1 with control (r = .420, p < .001) and guided evaluate (r = .255, p = .033) conditions. Also, there was a significant correlation for Problem 2 with the control condition (r = .494, p <.001). However, there were no significant correlations for Problem 3 across each of the conditions. Hence, a significant linear relationship between argumentation and conceptual quality may be attributed to problem topic/context. Although results suggest that correlations between argumentation quality and conceptual quality are problem dependent and condition dependent, the null hypothesis is rejected for Problems 4 and 5.

Table 15

Pearson Product Moment Correlation between Argumentation and Conceptual Quality Scores

	Control	Guided Construct	Guided Evaluate
Problem 1	r = .420, p < .001	r = .121, p = .317	r = .255, p = .033
Problem 2	r = .494, p < .001	r = .234, p = .051	r = .187, p = .121
Problem 3	r = .222, p = .065	r = .099, p =.416	r = .189, p = .118
Problem 4	r = .599, p < .001	r = .263, p = .028	r = .414, p < .001
Problem 5	r = .464, p < .001	r = .273, p = .022	r = .306, p = .010

Note. Problem 1 – Work and energy; Problem 2 – Law of conservation of energy; Problem 3 – Law of Conservation of linear momentum; Problem 4 – Force and impulse; Problem 5 – Gravitation and Newton’s III Law

Relationships between Condition, Pre-Conceptual Understanding, and Gender on Argumentation Quality and Conceptual Quality

The fifth null hypothesis was developed to test for relationships between students' pre-conceptual understanding (as measured by the FMCE score), gender, condition argumentation quality and conceptual quality scores across multiple topics. To examine these relationships, multiple regressions were utilized with FMCE scores, gender, and condition as predictor variables and argumentation quality and conceptual quality scores as criterion variables. A summary of all multiple regression analyses for argumentation quality and conceptual quality is reported in Tables 16 and 17 respectively.

A standard multiple regression analysis for Problem 1, using FMCE scores, gender and condition as predictor variables and argumentation quality scores as the criterion variable, revealed that condition, FMCE score, and gender significantly predicted argumentation quality, accounting for 21% of variance [$R = .459$, $R^2 = .210$, adjusted $R^2 = .199$, $F(3, 206) = 18.28$, $p < .001$]. The standard multiple regression for Problem 2, with argumentation quality as the criterion variable, revealed that only the condition predicted argumentation quality, accounting for 21% of variance [$R = .460$, $R^2 = .212$, adjusted $R^2 = .200$, $F(3, 206) = 18.45$, $p < .001$]. The standard multiple regression for Problem 3, with argumentation quality as the criterion variable, revealed that only the condition and gender predicted argumentation quality, accounting for 13% of variance [$R = .364$, $R^2 = .133$, adjusted $R^2 = .120$, $F(3, 206) = 10.50$, $p < .001$]. For Problem 4 the standard multiple regression, with argumentation quality as the criterion variable, revealed again that only the condition and gender predicted argumentation quality, accounting for 18% of variance [$R = .423$, $R^2 = .179$, adjusted $R^2 = .167$, $F(3, 206) = 14.93$, $p < .001$]. Finally for Problem 5 the standard multiple regression, with argumentation quality as the criterion variable, revealed again that the condition and gender predicted argumentation quality, accounting for 11% of variance [R = .357, R^2 = .128, adjusted R^2 = .115, F(3, 206) = 10.05, p < .001]. These results indicate that condition do contribute to argumentation quality. Additionally, depending on the problem context, the FMCE scores and/or gender can also contribute to participants' argumentation quality (Table 16).

A standard multiple regression analysis for Problem 1, using FMCE scores, gender and condition as predictor variables and conceptual quality scores as the criterion variable, revealed that condition, FMCE score, and gender predicted conceptual quality, accounting for only 9% of variance [R = .306, R^2 = .094, adjusted R^2 = .081, F(3, 206) = 7.100, p < .001]. The standard multiple regression for Problem 2, with conceptual quality as the criterion variable, revealed again that the condition, FMCE score, and gender significantly predicted conceptual quality, accounting for 7% of variance [R = .257, R^2 = .066, adjusted R^2 = .052, F(3, 206) = 4.860, p = .003]. The standard multiple regression for Problem 3, with conceptual quality as the criterion variable, revealed none of the predictor variables significantly predicted conceptual quality [R = .121, R^2 = .015, adjusted R^2 = .000, F(3, 206) = 1.03, p = .381]. For Problem 4 the standard multiple regression, with conceptual quality as the criterion variable, revealed that only the condition predicted conceptual quality, accounting for 5% of variance [R = .221, R^2 = .049, adjusted R^2 = .035, F(3, 206) = 3.54, p < .016]. Finally for Problem 5 the standard multiple regression, with conceptual quality as the criterion variable, revealed that none of the predictor variables predicted argumentation quality [R = .173, R^2 = .030, adjusted R^2 = .016, F(3, 206) = 2.13, p = .098]. Except for Problems 3 and 5, these results indicate that condition does contribute to conceptual quality. Additionally, depending on the problem context, the FMCE scores and gender can also contribute to participants' conceptual quality (Table 17).

Table 16

Summary of Regression Analysis for Variables Predicting Argumentation Quality for Each Problem

Variable	B	St. Error B	β
Problem 1			
Condition	.703	.106	.410**
FMCE	.019	.009	.135*
Gender	.636	.223	.182*
Problem 2			
Condition	.758	.105	.445**
FMCE	.004	.009	.031
Gender	.422	.221	.121
Problem 3			
Condition	.551	.106	.337**
FMCE	.005	.009	.040
Gender	.476	.222	.143**
Problem 4			
Condition	.621	.101	.389**
FMCE	.009	.008	.073
Gender	.532	.211	.164*
Problem 5			
Condition	.543	.114	.312**
FMCE	.020	.009	.142*
Gender	.455	.238	.128

*Note.** $p < .05$, ** $p < .001$; Problem 1 – Work and energy; Problem 2 – Law of conservation of energy; Problem 3 – Law of Conservation of linear momentum; Problem 4 – Force and impulse; Problem 5 – Gravitation and Newton's III Law

Table 17

Summary of Regression Analysis for Variables Predicting Conceptual Quality for Each Problem

Variable	B	St. Error B	β
Problem 1			
Condition	.198	.074	.176*
FMCE	.012	.006	.136*
Gender	.55	.156	.242**
Problem 2			
Condition	.181	.074	.165*
FMCE	.015	.006	.168*
Gender	.319	.155	.142*
Problem 3			
Condition	.098	.065	.105
FMCE	.002	.005	.032
Gender	-.078	.136	-.041
Problem 4			
Condition	.217	.093	.159*
FMCE	.013	.008	.120
Gender	.346	.195	.124
Problem 5			
Condition	.051	.001	.038
FMCE	.017	.008	.161*
Gender	.269	.192	.099

*Note.** $p < .05$, ** $p < .001$; Problem 1 – Work and energy; Problem 2 – Law of conservation of energy; Problem 3 – Law of Conservation of linear momentum; Problem 4 – Force and impulse; Problem 5 – Gravitation and Newton's III Law

Qualitative Phase

The qualitative results are organized around each of the research questions to address the emergent themes and case profiles (for the control, guided construct, and guided evaluate conditions) describing each emergent theme for each question. Representative quotes and written responses from each case are used to illustrate each emergent theme.

RQ 1: How Undergraduates' Solve Argumentative Physics Problems

Results reveal a total of eight emergent themes pertaining to how participants solve problems supporting alternative forms of argumentation. As illustrated below, the analyses show that each of the three conditions shared four central themes: (i) driven by views of argumentation, evidence, knowledge, and nature of physics; (ii) cued on problem features to develop solution strategy; (iii) influenced by alternative conceptions; and (iv) influenced by personal beliefs and confidence to solve and justify. Additionally, there were four themes unique to conditions which include: (v) variability in offering counter-arguments, (vi) usefulness of argumentation prompts, (vii) importance of argumentation prompts and hypothetical pseudo statements, and (viii) audience limiting justification. The sections below describe each emergent theme in relation to each case (control, guided construct, and guided evaluate) with illustrative excerpts.

Driven by Views of Argumentation, Evidence, Knowledge, and Nature of Physics

Arguments that participants generated in each case were influenced by their views of what argumentation is, what they perceived as useful or convincing evidence to justify proposed solutions, their views of knowledge or truth, and the nature of physics.

Views of control condition. Participants in the control condition seemed to view argumentation as an exchange in which an opinion supported with facts is offered and an opposition challenges the offered idea. Specifically, according to these participants, argumentation requires more than one side to engage in the process. Further, argumentation can only occur when the solution outcome is uncertain and there can be a disagreement of an issue.

> Argument, you have I guess your opinion but also it needs to be backed up by fact. It's like debating each other. In an argument there they are usually opposing each other. They should provide factual information although arguing sometime is people's opinions, but I think arguing it's more concrete and believable if it's real facts instead of opinion. (Abby, Interview 2, March 7th)

As Abby suggested, argumentation is an exchange between people using facts or opinions. Additionally, the participants seemed to suggest that an argument was believable or convincing if it was supported with facts or evidence and not opinion.

Participants perceived evidence as a rationale that is universally accepted or applied to support a proposed argument. For instance, Adan described, "Evidence is something that implies either cause or result. It implies some fact that's true. It's something that you could show someone else and they would reach the same conclusion that you did" (Interview 2, March 13th). Specifically, evidence in physics can take the form of a physics equation that matches the given problem information, a targeted concept or definition of a physical concept, information within a problem statement, a diagram indicating relations of interactions from the problem statement, observations or real-world experiences, and authoritative knowledge from the instructor or textbook. Interestingly, for these participants, evidence could also include common sense or their intuition regarding the problem scenario.

Participants seemed to view physics as explaining why things happen in the physical world. Knowledge or arguments pertaining to physics were perceived as true if they were justified with authoritative knowledge, observations or real-world experiences, application of a physical concept, or application of a physics equation. Additionally, an argument was perceived as true if one applied multiple approaches to solving the problem and continually reached the same answer. The utilization of physical concepts is perceived important since concepts are viewed as right or known and known how to use or apply. However, these participants seemed to perceive examining or applying physics equations as more convincing evidence than physical concepts. This was because physics equations were known, offered known relations and right answers to a problem, and related to real-world experiences. Concepts, on the other hand, were viewed as different from equations in that they could be manipulated to apply to problem cases. To illustrate this idea, Amber described an equation as, "it's telling you the answer, it's just saying how, why is that why, so you know the right answer and you're just using the information to explain why it's that way" (Interview 2, March 7th). Thus, relations of variables within equations encapsulated reasoning about the physical world, which one could then apply to problems to provide right explanations. Finally, the participants viewed physics equations as important because of their notions of the classroom or learning goals and what they were assessed on.

Participants' formula-centered notions of solving problems and constructing physics arguments seemed to challenge how they view the argumentative physics problems. Thus, the participants appeared to view these problems negatively because they were unable to apply numbers to solve for a definite answer. Indeed, the argumentative physics problems lacked numeric problem information and detailed problem information that one could find in traditional textbook physics problems. Thus, these problems needed participants to consider assumptions to solve the problem. Hence, participants expressed their preference to have more structured problem information, which might have allowed them to apply physics equations.

Views of guided construct condition. Participants in the guided construct condition viewed argumentation as an exchange of facts between two or more individuals or a one-sided exchange of ideas with oneself. As Blake explains during the second interview:

> An argument is a presentation of facts. The thing with an argument though is that it can be one sided or it can be two in a sense. An argument is just, I guess, putting forwards the facts so there doesn't necessarily have to be two people there. (Blake, Interview 2, March 14th)

Similarly, Blaise also describes argumentation are stating positions with a supporting rationale. As Blaise describes, "an argument to me, needs to, it could state its position, and identify the position they're trying to refute and it needs to have clear reasoning and clear ideas" (Interview 2, March 8th). Specifically, argumentation consists of stating a position with rationale as well as stating an alternative position with rationale. Results suggest that the participants overlooked the notion of a rebuttal in argumentation and instead focused their attention toward statements of positions and their rationale. To these participants, an argument in physics required presentation of facts or evidence to support theories or positions. As Blake continued to explain, "you'd have to have an authority to look at it and decide which ones were actually facts and which facts will apply correctly. In the case of our physics homework, it is whoever is grading it" (Interview 2, March

14th). Thus, to these participants, argumentation needed an authority figure to decide what was fact or acceptable evidence and if the facts or evidence were applied appropriately.

These participants seemed to regard evidence as physical, tangible, or observational and was a rationale that others could apply to arrive at the same answer (e.g. applying an equation in a similar manner to obtain the same results as a predecessor). In physics, according to these participants, evidence could include physical laws, theories, or concepts. Blaise expresses this notion when he states, "When I'm thinking of evidence, I'm thinking of things like theories, equations, and physical laws and things like Newton's laws and things like that" (Interview 2, March 8th). In another interview, Blaise elaborated his view of evidence as:

> Evidence is something like an equation or something like a concept that you use that directly relates to what the problem is asking or what's happening in the problem. Like in this case, one student struggled to move it and both participants struggled moving the red disc, so I talked about why they struggled. (Blaise, Interview 3, April 15th)

Here, Blaise explained that evidence should relate to the problem and can be applied to create an explanation. Generally, according to these participants, the physical concepts utilized for a problem were only those which are current in the course discussion or homework set. Also the physical laws were accepted as true in order to continue problem solving. Additionally, evidence could include physics equations that related to the given problem information, classroom demonstrations or laboratory experiments, real-world experiences, as well as authoritative knowledge. Similar to the control condition, physics equations were viewed as an important form of evidence and tool to aid in problem solving. More poignantly, participants viewed equations as factual relationships between variables and provided right answers. Interestingly, unlike participants in the control condition, participants in the guided construct condition did not seem to consider common sense or intuition as evidence.

Although participants in the guided construct condition describe the importance of evidence and what could be considered evidence, they tended to have a generic idea of applying evidence to justify their arguments. Specifically, if they identified a counter-argument for a problem, they seemed to have a tendency to rebut the argument by restating their own solution and explaining why their solution was correct or generically stating how they would convince others with an equation, diagram, experiment, or concept to justify their position. However, they tended not to state explicitly what equation, diagram, experiment, or concept they would use or how they would apply the proposed evidence to justify their position. For instance, the following conversation occurred while discussing Problem 3 (momentum conservation) of the homework:

> Interviewer: If someone disagreed with your solution, how could you convince them that your solution is true?
>
> Brice: I would give my equations and plug-in numbers. (Brice, Interview 2, March 8th)

During the interview, Brice described the conservation of momentum and conservation of energy equations and how they apply to his position that the steel block would take off faster. He said that if he were to rebut the alternative position that the wooden block would take off faster, he suggested that he would simply re-establish his rationale with the equations and further elaborate his justification by plugging-in numbers. However, he did not elaborate on how the equations would be used, what numbers would be used, and how the outcome could be interpreted or applied to the support his argument.

Participants in the guided construct condition recognized that there are different ways to solve physics problems; suggesting that there are tentative ways to approach how to solve a problem or what physical principles could apply. Similar to the control condition, there was a tendency for participants in the guided construct condition to refer to formula-centered approaches to solving the argumentative physics problems. Yet, they seemed to recognize that these problems do not necessarily require an equation to solve and may require additional problem information for which they need to develop assumptions. Such notions seemed to challenge how these participants viewed argumentative physics problems. Specifically, participants, like Bailey, expressed their preferences for more structured problem information, similar to those problems that they had experienced in their course or homework sets, which would allow them to apply equations. As Bailey explained, "I think in general, I always want to know things like mass, because like mass is important for like every equation" (Interview 2, March 7th). Additionally, they seemed to view an argumentative physics problem as being too much work to solve conceptually. Therefore, when they encountered these problems on the homework they neglected to solve these problems or not offer detailed or elaborate justifications of their solution. As evidenced by Bailey, "I didn't do these problems because it just seems like way too much work for ten points" (Interview 2, March 7th).

Views of guided evaluate condition. Participants in the guided evaluate condition seemed to view argumentation as having no right answer. They also viewed argumentation as a process of offering a position with supportive reasoning and offering counter positions with supportive reasoning. For example, Cayden described argumentation as:

> Two conflicting sides with evidence that supports both and evidence that just doesn't support both and there's no, there may be a clear answer but typically when we think about argument there is no right answers, just people bickering back and forth. (Cayden, Interview 3, April 4th)

These participants appeared to believe that argumentation requires at least two individuals with two conflicting sides. Here, Cayden suggested the notion of inducing disconfirming evidence within argumentation. Additionally, he continued on to describe that argumentation could occur in physics if one individual was deemed wrong about their problem solution. Participants described the role of evidence in an argument. As Cayden stated:

> Evidence, I mean I think its main role is to say why. In this kind of scenario where it's one or the other, it's kind of easier to say why the one that is incorrect is incorrect, then why the one that's correct is correct. It seems kind of like how evidence is used universally to prove or disprove something. (Cayden, Interview 2, March 7th)

These participants viewed evidence as reasoning to support a claim, relates to the problem statement, and further stated that evidence should be considered universally accepted, as evinced in Cayden's above statement. In particular, evidence should demonstrate how you arrived at a solution. Another participant, Carson described, "evidence in physics is like a toolbox, you can use them in anyway. However, evidence can potentially be misused. You can't use a hammer to screw in a bulb" (Interview 3, March 9th). According to these participants, evidence in physics could include physics equations or a numerical result from an equation; physical concepts, theories, or laws; assumption made; authoritative knowledge; problem information; and experimentation. Interestingly, similar to the control condition and unlike the guided construct condition, intuition could be viewed as acceptable evidence.

Despite how participants in the guided evaluate condition viewed evidence and what evidence can be, they tended to have a generic idea of applying evidence to justify their arguments. If they identified a counter-argument for a problem, they showed a tendency to rebut the argument by restating their own solution and why their solution was correct or generically stating that they would convince others with an equation, diagram, experiment, or concept to justify their position. However, they tended not to explicitly state which equation, diagram, experiment, or physical concept they would use and how they would apply the proposed evidence to justify their position. For instance when probed in an interview with Cayden about how he would rebut a counter-position, he stated, “I could talk about the conservation of momentum like I tried to here and say that I’m applying it and that this has to be true” (Interview 1, February 22nd). Here, Cayden identified a physical concept to apply to a problem, one which he had used previously to justify his position; however, he did not elaborate how conservation of momentum could be applied to a counter-argument. Additionally, he offered the notion that because it is a physical concept it must be true and that everyone should accept it as such.

These participants viewed physics as offering definite or right answers to problems. As Cedric states, “I feel like in physics it’s more like definite like there is a right and a wrong answer” (Interview 2, March 15th). Participants also suggested that physics knowledge is tentative in that the knowledge or problem solving approach can vary among problems. Specifically, they mentioned that there were different ways to solve a physics problem – either conceptually or with formulas. They recognized physics knowledge as true if it was authoritative knowledge, such as an equation, They viewed equations as explaining known variable relationships and further stated that if one plugged in numbers into the right equation variables, you would get definite answers. They also considered solutions to be true if there were no other alternative ways to solve the problem. A solution or argument could also be deemed true if it compared well with the hypothetical pseudo statements that used appropriate physical concepts.

Finally, participants in the guided evaluate condition viewed the argumentative physics problems as more conceptual problems not requiring computational problem solving strategies. Additionally, they seemed to recognize that these problems tend to need additional problem information and lack numerical problem information to solve the problem easily or efficiently.

Cues on Problem Features to Develop Solution Strategy

Participants seemed to attend to surface features within a problem statement or picture offering a means to extract pertinent problem information, identity physical concepts or equations and qualitatively describe the proposed arguments. Additionally, surface features also aided participants in deciding which problem solving strategy one may employ for a given problem.

Control condition. Participants in the control condition often focused on problem features to extract keywords or facts in order to aid in identifying target concepts. The following conversation with Adan as he discussed how he approached Problem 2 (energy conservation) of the homework illustrates this point:

> Adan: So the question is, you have – you’re skateboarding down a certain height and your and your friend is taking different ramps, different paths. So I immediately jump to energy is conserved, so potential will turn into kinetic. Because same height, it will end up being same velocity.
>
> Interviewer: Okay. What made you think of energy?

> Adan: Because the skateboard will be in motion. You are going form something that isn't moving with height and you're going – you're taking away that potential and turning it into something else. (Adan, Interview 2, March 13th)

While Adan was discussing how he approached Problem 2 of the homework, he described his attention to the object motion and height presented within the problem statement. The information that he has extracted from the problem had cued him to think in terms of conservation of energy. Participants can group of classify physics problems as a certain types of problem (e.g. a gravitation problem) in which one needs to apply a specific concept or equation. Additionally, participants can translate keywords within a problem statement to variables that aid in the identification of a particular physical concept or equation. Proposed solutions or arguments often consist of a qualitative description of problem surface features and may serve as the basis of their solution.

Throughout the study, participants in the control condition did not freely express a possible counter-argument to their proposed argument. However, when probed during the interviews about whether they could identify a possible counter-argument, they tended to refer to problem features as a means of creating a possible solution. Specifically, they may focus on a specific problem feature (e.g. distance) in which they may have made an assumption about what could affect the outcome of the solution they had created. For instance, if they proposed an argument in which they assumed the distance was relatively short, they may also propose a possible counter-argument someone may provide in which they assumed the distance was relatively large.

Guided construct condition. Participants in the guided construct condition also often focused on problem features to identify possible concepts or equations that could be applied for a given problem. These participants categorized problems or problem types as relating to certain physical concepts. Keywords within the problem statement may have cued participants to help them identify categories or problem types. Once they had identified a concept as being applicable, they identified the applicable equations as well. To illustrate this point, while Blaise was solving the Problem 2 (momentum conservation) from the interviews he said:

> Blaise: Okay, this looks like a conservation of momentum problem. It looks like, Jessie here is going to throw his ball and Jamie is – it doesn't specify in the problem but I, while answering I'll discuss Jamie catching the ball and what happens when there is a catch like that I'll discuss when if the ball hits Jamie and it bounces off her because those are both different situations of momentum conservation. I know that in either case Jamie moved to the left.
>
> Interviewer: Okay. What made you think of momentum conservation?
>
> Blaise: Well the problem states that there is a ball being thrown directly at someone else and since they're on a nearly frictionless frozen lake there will be some motion of the movement afterwards, everyone is stationary. So whether she catches or drops the ball we're going to be moving backwards. I know that from just what's been stated in the problem so t that's what makes me think about it as a momentum problem. (Blaise, Interview 2, March 8th)

Here, Blaise had classified the problem as a conservation of momentum problem which he appeared to establish by cueing on keywords (e.g. ball thrown at someone, frictionless) that described the problem scenario. Once he identified that the problem related to conservation of momentum he began to treat the problem like a collision problem and created a solutions pertaining to elastic and inelastic collisions with the ball. Participants also related equations to a particular problem by eliciting keywords for the problem statement, translating these words into variables and mapping these variables to the equation.

Not only did problem features aid in facilitating participants to identify concepts or equations, these features also aided the participants in creating assumptions about the problem statement. Further, the arguments proposed by the participants often consisted of qualitative descriptions of problem features, which were the focus of their solution. Specifically, instead of applying a physical concept or equation to develop a solution, participants might have solely relied on examination of problem features paired with their intuition to develop a solution. For instance, while describing how Problem 2 (energy conservation) of the homework was solved, Blake states:

> Blake: Okay. This one I said that both people you and your friend wouldn't reach the bottom going at the same speed, but that you would reach the bottom first. The reason being is that your slope, your change in height would change more quickly so you would reach a higher velocity more quickly. And in the long run that would cause you to end up at the bottom more quickly than your friend.
>
> Interviewer: Can you think of an alternative solution that someone could have or alternative argument?
>
> Blake: Yeah. The alternative I came up with was that somebody would say that your friend would reach there first. Their reasons and their supporting evidence is that they travel a shorter distance. And you'd have to assume that the picture is drawn to scale in order to actually be correct. (Blake, Interview 2, March 14th)

Here, Blake's argument focused on the problem feature - curvature of the tracks and distance – in which he applied his intuition in order to arrive at an understanding of the problem. Additionally, he established a possible counter-argument by assuming the distance as seen in the problem.

Guided evaluate condition. Attention to problem features also served those in the guided evaluate condition as a way to elicit keywords or problem information to aid in identifying relevant physical concepts or equations. For example while discussing how

Callie went about solving Problem 4 (momentum and impulse) of the homework she stated, “Well I say that the haystack like gave a smaller force over a longer period of time, therefore causing less damage to people, because like there is so many air pockets in a bale of hay” (Interview 2, March 5th). Callie suggested that the identification of differences in time impact is due to the structural features of the object into which one collides. Thus, the identification of time as a variable allowed Callie to apply the concept of impulse in her argument. Participants often examined the hypothetical pseudo debate arguments for keywords or differences in what’s said in the problem statement to assist them in deciding upon a solution strategy. Also, like participants in the control and guided construct conditions, the participants in the guided evaluate condition proposed arguments that consisted of qualitative descriptions of problem features which were the focus of their solution. Specifically, instead of applying a physical concept or equation to develop a solution, they paired their examination of problem features with their intuition to develop a solution. Additionally, they also utilized problem features to develop a possible counter-argument to a problem.

Influenced by Alternative Conceptions

Alternative conceptions can influence how individuals solve argumentative physics problems and the conceptual quality of the arguments proposed. At times, when participants cued on certain problem features, these features facilitated the application of their alternative conceptions on how to solve the problem. Specifically, by relying on a problem’s surface features as opposed to the underlying physical principles of the problem, the participants might have misidentified an appropriate physical concept or equation needed to solve the problem.

Control condition. Although participants in the control condition might have identified a physical concept to apply to a problem, they might have not appropriately applied the concept. Alternatively, they might have identified an appropriate physical concept but they might have applied or reasoned with the concept inappropriately. Amber's written argument to Problem 3 (momentum conservation) of the homework illustrates this point:

> The wooden block will take off faster after the collision. The bullet bounces off elastically with the steel block with result in the steel block having a velocity of 0 m/s. This is proved using the conservation of momentum. If the bullet has the same speed at the collision as before then the steel block will have the same velocity it had before the collision. The bullet that embedded into the wooden block will cause the block and bullet to move to the right based on conservation of energy. The final velocity of the block and bullet after the collision is equal to the square root of the mass of the bullet times the initial velocity of the bullet all divided by the mass of the wooden block plus the mass of the bullet. Giving a velocity greater than 0 m/s. (Amber, Interview 2, March 7th)

Here, Amber appropriately identified the concept of conservation of momentum. However, she misapplied the concept which led her to the incorrect conclusion that the steel block would not take off faster. Later, she inappropriately identified the concept of conservation of energy to apply to the problem. Applying conservation of energy led her to the conclusion that the wooden block would take off faster after the collision. A more physically correct response would have included the reasoning that the steel block would move faster than the wooden block after of the collision due to the steel block receiving twice the momentum transferred from the bullet during the collision.

Guided construct condition. Similar to the control condition, participants in the guided construct condition may have identified a physical concept or equation that was inappropriate to use for the problem. Alternatively, they may have identified an appropriate concept or equation but applied it inappropriately. Also, participants may have constructed an argument solution consisting of the misconception that the problem was designed to target. For example, Bailey's written argument to the first interview question (energy conservation) states:

> Bob's shot hits the ground faster because his bullet is coming directly from the gun with all the force from propulsion plus gravity. Bills bullet loses its propulsion force when it stops in the air before coming back down, leaving only gravity for speed. (Bailey, Interview 1, February 22nd)

For this problem, Bailey's argument is indicative of the misconception that an object will hit the bottom faster because it attains a direct downward velocity and travels a shorter distance. A more physically appropriate response would have included that both bullets reach the ground at the same speed due to conservation of energy. Alternatively, some participants provided counter-arguments within their justifications, but the counter-arguments might have in fact included the misconception that problem was design to target.

Guided evaluate condition. Similar to participants both the control and construct conditions, participants in the guided evaluate condition identified a physical concept or equation that was inappropriate to the problem or identified an appropriate concept or equation but applied it inappropriately. Participants' also were unable to identify relationships among physical concepts, such as the relationship between work and kinetic energy. Callie's written argument to Problem 1 (work and kinetic energy) of the homework illustrates this point:

> Neither Bill nor Bob is correct. The work of the two sleds would be equal this is because both of the work's would be the same. The kinetic energy, however, is not the same for both of the sleds. The heavier sled would have a higher kinetic energy than the sled with the lesser amount of mass. If a classmate were to come to me supporting either of the two argument I

> would explain to them that the sleds would have equal works. This is because work is just force multiplied by distance. Because of this the works are the same however the kinetic energies are different. (Callie, Interview 2, March 5th)

Although Callie's statement about equal amount of work is physically correct, her statement about kinetic energy is not. In fact, she offers little reasoning as to how she arrives at the notion of different amount of kinetic energy except for the statement about varying mass. She appears to allude to the idea that kinetic energy is equal to ½ mv^2. A more physically correct response would include the idea that both objects have the same amount of kinetic energy due to the principle that kinetic energy is equal to the change in work, which is the same. This observation consistent with the results of Lawson and McDermott (1987) who found that most participants are unable to use the work energy theorem, which states that the net work done on an object by all forces is equal to the its change in kinetic energy.

Influenced by Personal Beliefs and Confidence to Solve and Justify

Participants' personal beliefs or "my-side bias" (Jonassen, 2011) also tends to influence the quality of their argument. Specifically, personal beliefs can influence whether or not participants consider counter-arguments within their written arguments and if so then how they develop or evaluate the proposed counter-arguments. Confidence about their understanding of physics and the appropriateness of their written solutions can also influence the manner in which they solve and conceptual quality of the written argument.

Control condition. Participants in the control condition expressed the view that they often do not consider alternative solutions to a problem while solving the problem or they were unaware that they should be doing so. Instead, they judged their own argument to be right and there could be no other correct way to solve the problem. If they identified a counter-argument, it was not physically correct. The participants lack of physics understanding, alternative conceptions, or assumptions based on problem features, seemed to influence the counter arguments. Additionally, participants perceived their written argument as summing up what they wanted to say. For example, when probed during the interviews if they could identify a possible counter-argument, typical responses included “No, I pretty much – as soon as I thought I figured this one out that’s all. I didn’t consider any other solutions (Adan, Interview 3, April 10th)” or “Yeah, they could [have a different perspective], like not everyone knows about physics so like they may not know Newton’s laws and just think the ball will go to the left (Amber, Interview 2, March 7th)” and also “Outside of different conditions, I don’t think it would necessarily be correct (Alfred, Interview 2, March 8th).”

As illustrated from these quotes, for participants to have a counter-argument to their own argument, they either needed to consider different conditions or apply inappropriate understanding or intuition as alluded to by Amber. Otherwise participants did not consider other possible outcomes or approaches to solving the problem as reflected in their written arguments and comments during the interviews.

Confidence in their own solutions also seemed to influence the quality of argument participants constructed. They might have view that the manner in which they solved the problem and the argument they arrived at is correct that there was no other identifiable way to solve the problem. Despite any potential lack of confidence in the appropriateness of their solution, when probed during the interviews, they tended to maintain that there was no other counter-argument to their problem solution, or if there were a counter-argument, it would lead to the opposite outcome of the problem.

Guided construct condition. Similar to the control condition, participants in the guided construct condition at times did not consider counter-arguments while solving. Instead they focused on the construction of their own solution which they deemed to be the correct solution. Results suggested that if participants were confident about the appropriateness of their claim and rationale they might not have offered a counter-argument or they might have refuted a proposed counter-argument by restating why their own claim was correct as opposed to specifically addressing the nature of the counter-argument. A description by Bailey of how she solved Problem 1 (energy conservation) in the first interview, illustrates the point:

> Briefly I thought maybe they could have been the same but I don't know like with the problem like this, I mean even thought I am not very good at this class like I feel like that I answered probably correct. I feel like it's probably correct enough that, like I wouldn't be able to figure out reasoning for them hitting the ground at the same time base on what is here. So therefore I feel like there is no other reason to think about. (Bailey, Interview 1, February 22nd)

Bailey's statement suggests that she views her own solution to be correct and since she cannot think of any reasons for an alternate outcome there is no need to state a counter-argument.

Additionally, if they were not confident in their own physics understanding or the appropriateness of a physical concept/equation that they had applied, it may have influenced how they approached solving the problem and the quality of the argument they constructed. For example, while discussing with Bailey why she did not complete answering the first homework problem (work and kinetic energy) she states:

> I don't know, I feel like we did an example like this in class. I don't even really know how to reason it. I feel like if there is no friction then they would both be doing the same amount of work but then the heavier one would have more energy but I really don't know. I don't really understand anything going on in this class. I just feel like I am on like the edge and I get like fringes of things and I'm just like, 'that could be the right answer,' I don't know. I could write an answer down but I don't have any evidence. (Bailey, Interview 2, March 7th)

For this problem, Bailey's statement suggests that due to her confidence in her own answer and not being able to connect any evidence to justify her response she refrained from offering an argument. This is despite the fact that she was partially correct in that the work would be the same.

Guided evaluate condition. Similar to participants in the control and guided construct condition, participants in the guided evaluate condition at times did not consider counter-arguments while solving the problem. Instead, they focused on the development of their own solution which they deemed to be correct. Cedric illustrates this point while describing how he solved Problem 1 (work and kinetic energy) of the homework and why he included no counter-position. .Cedric stated, "I just went to straight to knowing that work is force times distance and same force and distance. That's what popped into my mind, so I just thought that was right and didn't go to any other solutions" (Interview 1, February 20th). As Cedric describes, he did not consider any alternative positions or problem solving strategies because he was confident in his own solution. Participants might have also perceived that if one offered a counter-argument, it would because the opposition did not think about the physics correctly. They might have also not considered incorporating a counter-argument in their written argument statement because they were more concerned about developing an easy, albeit simplistic justified solution. Results also suggest that if participants were confident about the appropriateness of their claim and rationale, they were more likely to refute a proposed counter-argument or the hypothetical pseudo debate arguments by restating their own claim and rationale for why it was correct. Also, if they were not confident about their own physics understanding or the appropriateness of the physical concept/equation that they applied, it may have influenced how they approached solving the problem.

Variability in Offering Counter-Arguments

Guided construct condition. Ascertaining possible counter-arguments can be influenced by several factors including an ability to identify how one could approach solving a given problem differently or logically obtaining an alternate solution. For instance, if they could not determine a rationale to support an alternative position, then they may not have forwarded that position as a counter-argument. Results also showed that the ability to identify potential counter-arguments depends upon the nature of the problem. Specifically, participants found it easier to recognize a counter-argument with some problems compared to others. For instance while Blaise was solving the fourth interview problem (rotational motion) he stated:

> Blaise: First I wrote about the equation for the force of gravity on two objects. The two masses are on the numerator of the equation, if either one of the two objects had been bigger, the force between them would have been larger. A possible counter-argument might argue that motion is independent of mass, by the force of gravity is force like any other, that is a mass times and acceleration, meaning more mass means a greater force.
>
> Interviewer: Okay. So now you discussed a possible counter-argument, what prompted you to do so this time, what made you feel like you could incorporate one?
>
> Blaise: It was easier for me to see that since it's a motion problem and a force problem, it was easier for me to see that might be two sides to it. (Blaise, Interview 3, April 5th)

Here Blaise describes that identifying a counter-argument is easier when he could identify two or more, clear possible concepts to apply to the problem. Additionally, if a problem included two possible outcome scenarios in which a respondent could choose from, then an identifiable counter-argument could be the opposite, non-chosen scenario. On the other hand, identifying counter-arguments could depend on belief bias or alternative assumptions one could make in regards to the problem variables based on the problem information or problem features which would influence the alternate outcome. Thus, participants seemed to recognize that based on one's assumptions their proposed solution could be correct. For instance while solving the fourth interview problem (rotational motion) Blake states:

> Blake: I said assuming the masses or the two discs are the same because strength didn't affect the ease of moving the disk. I would say that the weight of the materials was probably the same but the mass were distributed differently. For example one could be a solid disk and the other could be more like a ring. This would affect the moment of inertia which would in turn affect the ease of rotating the disk.
>
> Interviewer: Is there an alternative argument that someone could have for the problem?
>
> Blake: The weight was evenly distributed and the red disc was a heavier material, just different assumptions. And really I wouldn't be able to explain to the classmate that my opinion was right, because they are based off of different assumptions. (Blake, Interview 3, March 14th)

Here, Blake describes two possible assumptions individuals could make – differences in mass distribution or differences in weight of the discs – each of which are physically appropriate assumptions that one could apply as the basis for an argument or counter-argument. Blake recognizes that based on which assumption one might choose, they would be no more correct than the other would. Participants' ability to recognize possible counter-arguments were also influenced by their understanding of physics and of the problem. For instance, participants may have offered a counter-argument by inappropriately applying a physical concept or by applying an alternate physical concept or equation related to the problem.

Guided evaluate condition. Similar to the guided construct condition, ascertaining possible counter arguments can be influenced by a participant's ability to identify how one could approach solving a given problem differently or an alternate solution someone could logically obtain. For instance, participants may be aware that someone could have a different position but are unable to identify what that might explicitly be. Also, in part due to their belief bias and their physics understanding, they may be unable to think of reasons how their solution could be perceived wrong or reinterpreted by a classmate. Additionally, the ability to identify potential counter-arguments can depend upon the nature of the problem. For instance, an identifiable counter-argument may emerge from other possible outcome scenarios in which a respondent may choose from or they may perceive one or both the hypothetical pseudo debate arguments as a counter-argument. On the other hand, identifying counter-arguments can also depend upon alternative assumptions which one could make about problem variables or problem features that can influence an alternate outcome. For example when Cedric described a possible counter-argument for Problem 1 (work and kinetic energy) of the homework he states, "A counter-argument could be if they didn't start with the same speed which the problem didn't state, then the final kinetic energies would be different" (Interview 1, February 20th). As indicated by Cedric's statement, an assumption could be based on creating a non-ideal problem scenario. For this problem, Cedric created a new assumption about the initial velocities of each sled as opposed to an ideal assumption that they start from rest as per which they each had no initial velocity. Also their understanding of physics and of the problem might have influenced whether they could recognize possible counter-arguments. For instance, they may offer a counter-argument by inappropriately applying a physical concept or applying an alternate physical concept or equation that may or may not relate to the problem.

Usefulness of Argumentation Prompts

Guided construct condition. Participants in the guided construct condition expressed the notion that their argumentation prompts to construct an argument were not useful. As reflected by Brice's statement, "I just don't understand the point of discussing those questions, so I don't bother with them. When I already got something I just write it down" (Interview 3, April 5th). The only prompt indicator they tended to focus on was making sure to offer evidence for their own position. Perceptions of the argumentative prompts could potentially be influenced by their belief bias or variability in offering a counter-argument. As Brice also explains "I don't know how someone would solve the problem. I'm not going to think of how other people think" (Interview 3, April 5th).

Importance of Argumentation Prompts and Hypothetical Pseudo Statements

Guided evaluate condition. Participants in the guided evaluate condition expressed the notion that their argumentation prompts could be helpful to reflect upon and further support their solution. They stated that the prompts helped them organize and make writing of a qualitative solution easier. However, the participants indicated that the prompts did not seem to help in problem solving. Also they express the notion that the hypothetical pseudo debate arguments were generally not useful, but if they were in doubt of how to solve a problem they could evaluate the hypothetical pseudo debate statements for keywords or differences in search for clues on how to solve the problem. For example, Carson explains, “not that is answer is hidden in what they [pseudo debate arguments] are saying, but that your answer should be about what they’re saying. It shouldn’t be something totally different” (Interview 2, March 9th). Thus, the hypothetical pseudo debate arguments may have guided and shaped the kinds of arguments participants may have constructed. The notion that the hypothetical pseudo debate statements were not useful was because through experience with the argumentative problems, the participants found that they usually did not agree with either of the statements. Thus, they realized that each pseudo argument may present flaws in their answer and/or reasoning. Therefore, the participants may have found it easier to solve the problem first and then examine the contents of each hypothetical pseudo debate argument. However, influenced by their physics understanding or alternative conceptions, they may have picked a hypothetical pseudo statement that they viewed as being a more correct argument between the two. The hypothetical pseudo debate statements also may have served as an easily identifiable possible counter-argument that someone may have.

Audience Limiting Justification

Guided construct condition. While writing their proposed argument, participants in the guided construct condition wrote to whom they perceived as the audience (e.g. the homework grader) for their arguments to the argumentative homework problems. As Blaise illustrated, “I think I assume that somebody reading this would have an idea of what conservation of energy is. I did not talk about it in great detail” (Interview 2, March 8th). Later Blaise goes on to state:

> I didn't bring up counter-arguments mainly because like I mentioned earlier about I mean just thinking that other people have a knowledge of physics like if this is the answer then this is, there's no rally other way of working around it. (Blaise, Interview 2, March 8th)

The participants seemed to assume the audience understood physics, such as the meaning of physical concepts, and could understand and evaluate their physics reasoning. Therefore, they perceived no real need to convince or elaborately justify their solution.

RQ 2: Problem Solving Strategies Utilized to Solve Argumentation Problems

Results reveal, that in total, participants employed 11 different problem solving strategies while solving problems supporting alternative forms of argumentation. The sections below describe each strategy as used by participants in each case (control, guided construct, and guided evaluate) with illustrative excerpts. Additionally, the problem solving strategies utilized by participants in each case condition for each argumentation problem are presented in Appendix N. As illustrated below, each of the three conditions employ the physical mechanism game, case reuse, covariational reasoning, and qualitative concept application strategies in similar ways. Strategies unique to conditions include: recursive plug and chug or hypothetical plug and chug, recursive concept testing, pictorial analysis game, extreme case thought experiment/comparing scenarios/generating scenarios, mapping meaning to mathematics, evaluation of problem cases, and constructing and comparing solutions.

Physical Mechanism Game

As described by Tuminaro and Redish (2007), individuals who use the physical mechanism game, do not make explicit reference to physical principles or equations while constructing solutions. Instead, they draw upon their intuition of the problem scenario or naïve understanding of a physical principle to construct a qualitative solution.

Control condition. Participants in the control condition often constructed arguments by applying their own intuition to the problem scenario or referring to real-world relations. They suggested that arguments need real-world relations as per their views of what constitutes evidence. When participants were unsure of how to solve a problem using physical principles or equations, they seemed to rely on their "gut instinct" or real-world experiences. They used their real-world experiences or gut instinct to solve the problem, and as evidence to their arguments. Participants generated arguments that incorporated qualitative descriptions of problem surface features paired with their intuition as rationale for a solution and outcome. For example, Alfred's written argument to Problem 2 (energy conservation) of the homework states:

> We will reach the bottom at the same time, but I will be going faster. This is because we both start at the same height, but my path allows for me to accelerate on the way down, his path is at constant velocity. So I will pick up more speed than him. However he has a straight path while mine is longer. This is why we will reach the bottom at the same time. (Alfred, Interview 2, March 8th)

Alfred's written argument and comments during an interview concerning this problem suggests he is applying intuition, opposed to any physical principles such as the law of conservation of energy, to predict the outcome of the problem based upon features of the problem, which in this case include the curvature and length of the skateboard tracks. In this case, by relying on intuition and surface features, Alfred incorrectly claims that the skateboarders with reach the bottom and the same time but the one on the down-ward curved track will travel faster.

Guided construct condition. Participants in the guided construct condition also tended to apply real-world experiences or common sense as a guide for their problem solving process and for constructing arguments. Solutions, such as that by Alfred (above), often focus on qualitatively describing surface features along with their intuition as opposed to applying physical principles or laws in their reasoning. Also, generated arguments could be influenced by their perception of the simplicity of the problem in which participants felt could best be answered with intuition alone. In some circumstances, participants who employed the physical mechanism game to solve argumentative problems would also continue to employ the same strategy to identify and provide rationale for counter-arguments. However, there were instances in other argumentative problems in which a participant may have employed another type of problem solving strategy but transitioned to the physical mechanism strategy to identify counter-arguments.

Guided evaluate condition. Similar to the control and guided construct conditions, participants in the guided evaluate conditions often employed their intuition or real-world experiences as a guide to solving argumentative problems. Here, participants solved and evaluated each of the hypothetical pseudo debate arguments with their intuition as opposed to employing physical principles. Similar to the guided construct condition, participants who employed the physical mechanism game to solve argumentative problems may have also continued to employ the same strategy to identify and provide rationale for counter-arguments. However, there were instances in other argumentative problems in which a participant may have employed another type of problem solving strategy but transitioned to the physical mechanism strategy to identify counter-arguments. If counter-arguments were included within their written arguments, participants may have offered rebuttals based on their intuition about the problem.

Recursive Plug-and-Chug or Hypothetical Plug-and-Chug

Tuminaro and Redish (2007) describe recursive plug-and-chug as solving for numerical answers by plugging quantities into physics equations. In this epistemic game, individuals begin by identifying relevant problem information and examine equations to look for the equation, which matches variables that they translate from the problem information.

Guided construct condition. A strategy that was unique to the guided construct condition that participants employed while solving argumentative problems is hypothetical plug-and-chug. In this strategy, a participant identified relevant problem information which translated to variables. Then, the participant targeted an equation that appeared to align with the variables identified from the problem statement. Although the argumentative problems lacked numerical problem information, the participant then assigned arbitrary numerical values to apply to the equation followed by an evaluation of the solution outcome. Generally, participants adopted this strategy if they were able to identify a relevant equation and yet were unsure of how to apply the underlying physical principles of the equation to the problem or be how to proportionally reason with the variables in the equation. Brice illustrates this point while solving Problem 1 (energy conservation) of the interviews:

> So we're looking for the speed at this point right here, so this one you – I'm assuming that I'm using the same rifle so the V0 for both rifles are the same. This one is fired up, this one is fired down. And I think that I'm going to use this equation from my kinematic equations. Because as final velocity and initial velocity and then I just need the time what it takes to hit the ground … But I don't need to find how much time it takes to hit the ground. For this one it's going to take longer time and this one is going to take short time. Deceleration due to gravity is same for both. And if I completely don't know how to solve discussing questions I usually just make up arbitrary values in point of the equation. So this fire from the

> same gun I'm assuming, so the initial velocity is only same. T1 is greater than T2, deceleration due to gravity is 9.8 and so we'll just put it in this equation. V0 will make this arbitrary value of the gun, 298 meters per second. And then T1 will make 2.5 seconds I'll make this one 1 second. And then from there I'll get V final and then in this case we'll get this one to be greater than this one. (Brice, Interview 1, March 8th)

Here, Brice is identified a kinematics equation and then employed this equation by creating arbitrary numbers not provided within the problem statement. By applying these numbers to variables in the equation, he inappropriately reasoned that Bill's bullet would travel faster.

Recursive Concept Testing

Control condition. A strategy that was unique to the control condition that participants employed while solving argumentative problems is recursive concept testing. In this strategy, a participant was able to identify a potentially relevant physical concept to be applied to the problem. Typically, they based their selection of a physical concept upon keywords or surface features within the problem that cued them to think a particular concept was relevant. Once a concept was identified, the participant applied the concept and generated a qualitative description of a solution. However, if the participant realized that it was either too difficult to apply the concept or the concept would not help guide them to a desired solution; they would then attempt to apply a new physical concept. A participant would recursively perform a trial-and-error analysis of concept until they reached what they perceived as an acceptable solution. For example, during an interview with Adan concerning how he solved Problem 4 (momentum and impulse) on the homework he stated:

> Okay, I looked at it in two different ways. I looked at it in terms of impulse, force and time and then also looked at it in terms of work, force,

> and distance and both ways I came up with the same answer. Therefore, my solution is correct. (Adan, Interview 2, March 13th)

Adan expressed that he was he was initially unsure how to solve the problem and had identified two potential approaches to it – use of impulse and work. Subsequently, he applied and tested both concepts and once he realized he had reached the same solution, he concluded that he had the right answer with either approach.

Case Reuse

Participants who employed case reuse developed solutions to new problems by utilizing previously worked examples (Jonassen, 2006) These individuals did not necessarily attain a conceptual understanding of the worked example but instead identified patterns that related to the given problem scenario in order to map the previous problem solution onto the new problem. This strategy is similar to the transliteration to mathematics (Tuminaro & Redish, 2007).

Control condition. For argumentative problems in which participants in the control condition employ case reuse, they applied classroom discussions, demonstrations, or previously solved examples that appeared to be similar to those problems. Based upon surface features of the given argumentative problem, they may have recognized patterns or similarities to problems they had previously experienced. Abby discussing how she approached Problem 1 (work and kinetic energy) of the homework illustrates this point:

> This one, there was a problem in the book that was about sailboats I think, starting on an icy lake and they took the same amount of energy to cross the lake, so then I knew the energies were the same. (Abby, Interview 2, March 13th)

Abby here describes how she recalled a similar problem from the textbook based on the problem information. Then, based on the solution to that problem she correctly concluded that the energies were the same in this problem.

Guided construct condition. Similar to participants in the control condition, participants in the guided construct condition also employed case reuse in which surface features of a problem aided them in identifying relevant problems or examples they previously experienced. As opposed to understanding the underlying physical principles of the previously experienced problems, these participants seemed to map solution patterns of those problems onto the new argumentative problem to solve them.

Guided evaluate condition. Participants in the guided evaluate condition may also employ case reuse which may be informed by surface features of the problem that aided them to identify relevant problem examples. Utilization of case reuse may have also been informed by their perceptions that it may be easier to think about other homework problems previously solved in order to map solution patterns onto the new problem. As they generated arguments, participants tended to apply previous classroom discussions, examples, diagrams, or homework. Additionally, analogies to other problem types may be employed in an attempt to map solution patterns from other problem types.

Pictorial Analysis Game

Participants who employed the pictorial analysis game while solving physics problems generated an external representation (e.g. free-body diagram or graphs) that guided their inquiry to construct a qualitative solution (Tuminaro & Redish, 2007). These representations illustrated the relationship between various influences in the problem statement.

Control condition. Participants in the control condition adopted the pictorial analysis game to visualize and to understand further the problem scenario or to express their arguments. By visualizing the problem they were further able to apply their understanding to the problem. They constructed a qualitative solution that linked the representation to their conceptual understandings. For example, to guide Adan's inquiry concerning Problem 5 (gravitation – Newton's laws) of the interviews, he constructed a picture (as seen in Figure 2) during the third interview representing the Earth and an asteroid in which he added an axis to describe the problem in terms of toque, gravitational pole, as well as linear and angular momentum.

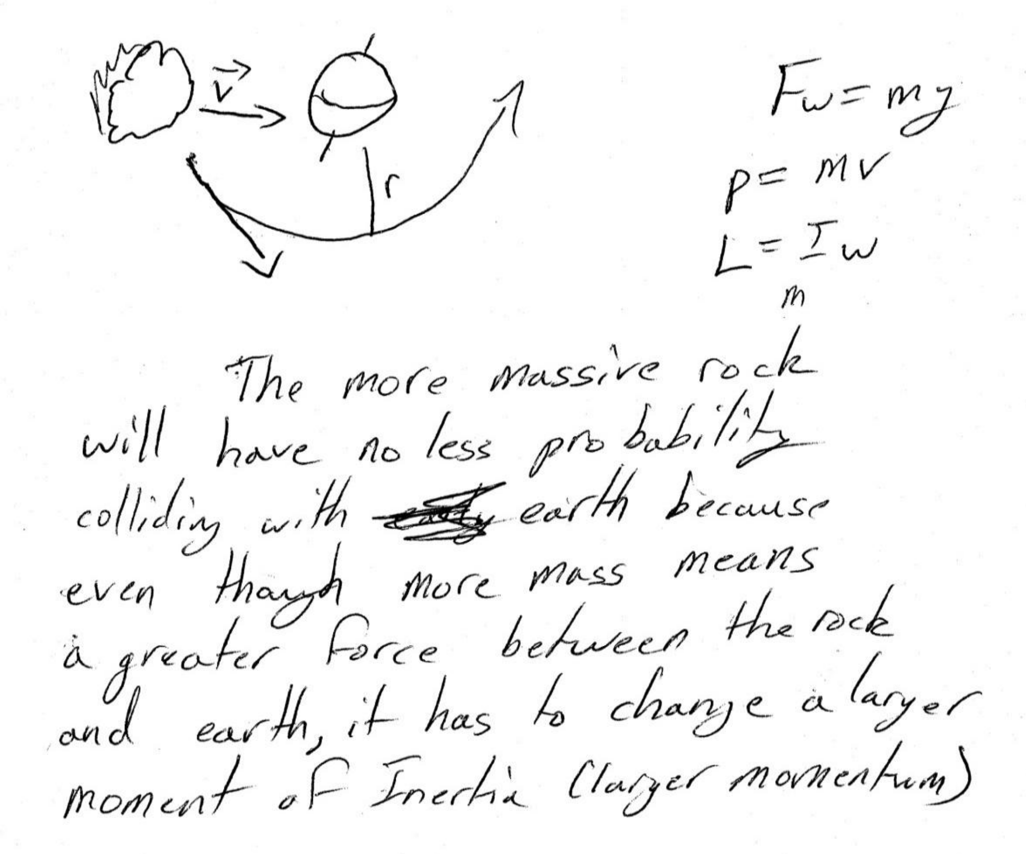

Figure 2. Adan's written solution to interview Problem 5 uses the pictorial analysis strategy

Guided evaluate condition. Similar to the participants in the control condition, participants in the guided evaluate condition also employed the pictorial analysis game to visualize the problem and further understand interactions within the problem. They then constructed a qualitative solution that linked the representation to their conceptual understanding of the problem.

Extreme Case Thought Experiment/Comparing Scenarios/Generate Scenarios

Participants employed the extreme case thought experiment as a strategy to aid in identifying a possible counter-argument, compare two or more likely scenarios prior to arriving at a solution, or as a means to generate more scenario options which could be utilized as potential counter-arguments. In this strategy, participants reduced a problem to extreme cases based upon the assumptions that they made concerning the problem information.

Guided construct condition. Participants in guided construct condition employed the extreme case thought experiment as a strategy to solve and further justify their constructed arguments. They viewed this strategy as a mechanism to convince others of their solution. In this strategy, they often made extreme assumptions regarding the problem information in order to create uniquely different problem outcomes. These outcomes could then be offered as possible counter-arguments or the participant could choose to compare these outcome scenarios to further aid them in deciding their own problem solution.

Guided evaluate condition. Participants in the guided evaluate condition employed the extreme case thought experiment as a strategy to solve and justify their written argument. They did so by reducing the problem to extreme cases or extreme assumptions of the problem to generate varying problem solutions. Some of the participants viewed this strategy as "the best way to solve" and clearly identify varying problem outcomes. Cayden's description of a possible an alternative argument for Problem 1 (work and kinetic energy) on the homework illustrates this point:

> They might think that velocities might be way different, based on what the mass is, you could say that. And the best way to go about things usually is taking them to the extreme and think about what happened if you push a really small sled or a sled that weighs like nothing, it might go like a 100 miles an hour if it weighs like nothing, but if you have a sled that weighs million pounds and push it, it's not going to go as fast, and they might say that because the velocity squared is kind of the dominant variable and it therefore would matter more than the mass. (Cayden, Interview 2, March 7th)

Here Cayden describes how the problem can be viewed by thinking of the dependent variable – velocity – in terms of extreme proportions to decide upon the outcome.

Covariational Reasoning

Covariational reasoning comprises comparing and contrasting cases in order to determine probabilistically that a certain case is the cause (Hung & Jonassen, 2006). In this sense, covariational reasoning can be employed as a strategy to predict solution outcomes and to aid in identifying possible counter-argument by comparing and contrasting variables within a mathematical relationship. For example, in continuation to Abby's discussion concerning Problem 1 (work and kinetic energy) of the homework she says:

> So, since it said here that, continuously pull out forces with exactly are sleds with exactly the same force, so that was easy because I knew "work is force times distance," and it didn't matter, which one was bigger. If they had the same force then I knew they're going the same distance then work was obviously the same. (Abby, Interview 2, March 13th)

Here, Abby described keywords extracted from the problem statement and translated these keywords into variables which she mapped onto the equation for work. Thus she was able to proportionally reason that work would be the same based on the provided information concerning each variable. As described below, each of the three conditions employed covariational reasoning for a given problem in a similar manner.

Control condition. Participants in the control condition qualitatively applied equations to predict and explain relations in instances in which problem information could be translated into variables and an equation was deemed relevant to the argumentative problem. The participants explored the causal relationships among variables within a mathematical expression to determine problem outcomes influenced by a particular variable.

Guided construct condition. Similar to the control condition, participants in the guided construct condition translated problem information into variables and applied those variables to an equation to predict the outcome of a problem. They may have identified an alternative argument by changing a variables based on varying the assumptions to influence the outcome of the problem.

Guided evaluate condition. Similar to participants in the control and guided construct conditions, participants in the guided evaluate condition explored the causal relationships among variables within a mathematical expression to determine problem outcomes influenced by a particular variable. They may have identified an alternative argument by changing a variables based on varying the assumptions to influence the outcome of the problem.

Qualitative Concept Application

Participants used the qualitative concept application strategy when they identified a physical concept, which they then applied to the problem case. The participant then constructed a qualitative argument describing how the concept was applied to the problem and how they arrived at outcome of the problem.

Control condition. Participants in the control condition employed the qualitative concept application strategy when they identified a concept, which they could then apply to the problem case. The definition or meaning of a physical concept was applied in order to qualitatively describe interactions of phenomena extracted from the problem information. A solution or argument then emerged from this qualitative description. Amber's written argument for Problem 5 (gravitation – Newton's laws) of the homework illustrated this point:

> The satellite does exert a force on the earth from its initial takeoff. The force exerted on the earth from the satellite is equal to the force exerted on the satellite from the earth. This is due to Newton's third law that every action has an equal and opposite reaction. (Amber, Interview 3, April 4th)

During the interview concerning this problem, Amber explained that from the problem information she was able to correctly identify Newton's III law as an applicable concept. As reflected in her written argument she qualitatively applied the meaning of the concept – Newton's III law – to the problem information.

Guided construct condition. Similar to participants in the control condition, participants in the guided construct condition employed qualitative concept application when they identified a concept in which they could then apply to the problem case. They applied the definition or meaning of a physical concept in order to describe qualitatively interactions or phenomena extracted from the problem information. A solution or argument then emerged from this qualitative description. Additionally, those who employed the qualitative concept application strategy to solve argumentative problems may also continue to employ the same strategy to identify and provide rationale for their counter-arguments. However, there are instances in other argumentative problems in which a participant employed another type of problem solving strategy but transitioned to the qualitative concept application strategy to identify counter-arguments.

Guided evaluate condition. Similar to participants in the guided construct condition, participants in the guided evaluate condition employed qualitative concept application when they identified a concept in which they then applied to the problem case. Participants applied the definition or meaning of a physical concept in order to describe qualitatively the interactions or phenomena extracted from the problem information. A solution or argument then emerged from this qualitative description. Additionally, some of the participants who employed the qualitative concept application strategy to solve argumentative problems also continued to employ the same strategy to identify and provide rational to counter-arguments. However, there were instances in other argumentative problems in which participants employed another type of problem solving strategy but transitioned to the qualitative concept application strategy to identify counter-arguments.

Mapping Meaning to Mathematics

As indicated by Tuminaro and Redish (2007), participants who utilized mapping meaning to mathematics began from a conceptual understanding of the problems scenario and progressed toward a quantitative solution. Specifically they translated problem information into mathematical quantities, developed a relationship or equation of the mathematical quantities, and evaluated and interpreted solution outcomes. Blaise's written argument to Problem 3 (momentum conservation) of the homework illustrates this point:

> In each of these situations, linear momentum is conserved by the bullet/block system. Whether the collision is elastic or inelastic, the linear momentum of the system is always conserved. In each case, the only linear momentum before the collision is in the bullet since it is the only object with a velocity greater than zero. After the collision, the block which takes off faster is the steel block which underwent an elastic collision. The reason for this can be explained using the linear momentum equations. If the initial linear momentum is equal to the final linear momentum, then the linear momentum of the bullet just before it hits the wooden block will be exactly equal to the linear momentum of the wooden block/bullet system after the collision ($mv = (m+M)V >> V = mv/(m+M)$, where V is the velocity of the block after the collision, m is the mass of the bullet, v is the velocity of the bullet, and M is the mass of the block). The linear momentum of the steel block will be exactly twice the linear momentum of the bullet just before it hits the block ($mv = -mv + MV >> 2mv = MV >> V = (2mv)/M$, where V is the velocity of the block after the collision, m is the mass of the bullet, v is the velocity of the bullet, and M is the mass of the block). Comparing the two values for the two blocks, it is clear that the linear momentum for the steel block will be greater than that of the wooden block ($mv/(m+M) < (2mv)/M$). Any argument using the conservation of energy is invalid in this situation since energy is never conserved in an inelastic collision (the bullet embedding in the wooden block) and energy is only conserved in perfectly elastic collisions (the bullet bouncing off of the steel block). The steel block underwent an elastic collision, meaning energy was lost in the process. (Blaise, Interview 2, March 8th)

As illustrated, Blaise began with a correct conceptual understanding of how conservation of momentum applied to the problem. He then translated information from the problem into variables to construct an equation that related the variables. Finally, he used this equation to justify his position.

Guided construct condition. The mapping meaning to mathematics strategy was unique to the guided construct condition while solving argumentative problems. Participants who employed the mapping meaning to mathematics strategy began by reading the problem statement, looking for keywords or problem features, and identifying an underlying physical concept. They then translated problem information into variables and developed a mathematical expression to describe the problem. Finally, they applied this mathematical expression to determine a solution and constructed argument to support this solution. Blaise' written response to Problem 3 (momentum conservation) of the homework illustrates this point.

Evaluation of Problem Cases

Guided evaluate condition. The evaluation of problem cases strategy was unique to participants in the guided evaluate condition while solving argumentative problems. In this strategy, the participants read and evaluated each of the hypothetical pseudo debate arguments to determine which of these may potentially be incorrect with regard to their solution and/or reasoning. Alternatively, participants examined the pseudo debate arguments for differences in their statements to help identify a relevant physical concept or equation that they then could apply to their argument development. Specifically, participants would focus on the reasoning in the pseudo statement to help guide their own argument construction. For example, while solving Problem 1 (energy conservation) of the interviews Cayden says:

> So, I basically I … I recognized that this was an energy question because they [pseudo debate arguments] were sort of talking about energy. So, I knew kinetic energy is going to play a part and towards finding it at the ground and I figured that the only difference is between these two scenarios, this is going up and going down, so that, that had to play a part. I guess it's also necessary to talk about all the potential energy that happens up there, because I mean it just gets transformed once it's here. So, I had to find the difference or to see if there was a difference in energy because that's what they are saying that it loses energy and this, like the, talks about energy, gaining height and says it'll have additional energy, but that's not true, it has a same amount of energy at that, at least, that's what I think. But, yes, I had to find the difference and I know that there is

> air resistance and that's non-conserving force, so that would relate mean of difference in energy at these points. So, and that's the same, so it's really the difference at these points is what mattered to find the solution. (Cayden, Interview 1, February 22nd)

In the interview, Cayden explained that he may approach a problem by examining differences in what each hypothetical pseudo debate argument contained. Also Cayden explained that he recognized that each hypothetical pseudo debate statement included a discussion of energy therefore; he concluded that this must be an energy problem. He further stated that he evaluated each statement to determine if he could find a plausible outcome from which he could construct his own argument.

It should be noted that while a participant may have employed the evaluation of problem cases strategy, they may also have employed other problem solving strategies in conjunction with this strategy. Specifically, problem solving strategies such as physical mechanism game, extreme case thought experiment, covariational reasoning, or qualitative concept application were applied along with evaluation of problem cases to provide a means of being able to evaluate problem cases and develop a solution.

Construct and Compare Solutions

Guided evaluate condition. The construct and compare strategy was unique to participants in the guided evaluate condition while solving argumentative problems. In this strategy, a participant first constructed their own argument based upon their own understanding and then compared their constructed argument to the hypothetical pseudo debate arguments to further justify their argument. This strategy tended to be employed more often than the evaluation of problem cases strategy when participants realized that the hypothetical pseudo debate arguments were not always useful to help them arrive at a solution. Participants who employed this strategy described that they more often tended to disagree with the solution or rationale within the pseudo debate arguments. Therefore, they believed it was easier to solve and construct their own argument first they can compare their argument to those of the pseudo debate arguments. This strategy allowed them to compare their own arguments with the pseudo debate arguments and offer rebuttals to the pseudo debate arguments which they perceived as possible counter-arguments.

It should be noted that while participants may have employed the compare and construct strategy, they may also have employed other problem solving strategies in conjunction with this strategy. Specifically, participants used problem solving strategies such as physical mechanism game, covariational reasoning, or qualitative concept application along with construct and compare to provide a means of develop a solution and compare their argument with those proposed in the hypothetical pseudo debate. Cedric's description how he approached Problem 1 (energy conservation) of the interviews illustrates this point:

> Neglecting air resistance it will have the same velocity downward at that point as it did going upwards at this point. And then since these two velocities are equal just in the opposite directions, this velocity right here would be the same as if you just shot it straight down, so then they would have the same energy when they hit the ground, because they are going at the same speed. Okay. Alright, so the problem with Bill's would be it's not gaining energy, it just transforming from kinetic to potential and then going back to kinetic. And then with Bob it's not working against gravity, because there is no force exerted on it, other than the weight itself, so that's the only thing doing work. (Cedric, Interview 1, February 20th)

As illustrated in Cedric's statement, he identified the concept of energy to qualitatively apply and create his own understanding of the problem. Only after he identified a correct solution to the problem – equal velocities – did he then refer to the pseudo statements by Bill and Bob in order to use them as an aid to justify his response.

RQ 3: Cross Case Analysis of Problem Solving Strategies

Tuminaro and Redish (2007) describe six problem solving strategies that students may employ while solving algebraic and conceptual physics problems in a second-semester algebra physics course. In this study, results indicate an alignment with strategies identified by Tuminaro and Redish (2007) such as physical mechanism game, recursive plug-and-chug, case reuse or transliteration to mathematics, pictorial analysis game, and mapping meaning to mathematics. Results of this study also indicate six additional strategies that students may employ with solving varying forms of argumentation problem in physics. These strategies are: recursive concept testing, extreme case thought experiment/generating scenarios, covariational reasoning, qualitative concept application, evaluation of problem scenarios, and constructing and comparing solutions.

Results of this study also showed that participants in each case condition (control, guided construct and guided evaluate) employed intuitive or formula-centered strategies. For instance, participants in the guided evaluate condition seemed to recognize that equations are useful to help solve problems even if you cannot plug numbers into them. However, participants in the control condition more often than participants in the other conditions tended to utilize personal intuition or formula-centered strategies. As illustrated by Alfred's quote, "I just solve like they were math story problems, pull facts from the problem and use equations" (Interview 2, March 8th).

Table 18 provides a cross case summary of problem solving strategies employed by participants in each case condition while solving argumentative physics problems.

Additionally, problem solving strategies utilized by each case condition for each argumentation problem are presented in Appendix N.

Table 18

Problem Solving Strategies Utilized by Participants for Each Condition to Solve Argumentative Physics Problems

	Control	Guided Construct	Guided Evaluate
Physical Mechanism Game	X	X	X
Recursive Plug and Chug or Hypothetical Plug and Chug		X	
Recursive Concept Testing	X		
Case Reuse	X	X	X
Extreme Case Thought Experiment/Comparing Scenarios/Generate Scenarios		X	X
Covariational Reasoning	X	X	X
Qualitative Concept Application	X	X	X
Pictorial Analysis Game	X		X
Mapping Meaning to Mathematics		X	
Evaluation of Problem Scenarios			X
Construct and Compare Solutions			X

As shown in Table 18, each case may employ physical mechanism game, case reuse, covariational reasoning, and qualitative concept application to a given argumentative physics problem. However, there are problem solving strategies that are unique to each case condition. For instance, participants in the control condition employed recursive concept testing or pictorial analysis game. However, participants in the guided construct condition employed recursive hypothetical plug-and-chug or mapping meaning to mathematics. Similar to participants in the control condition, participants in the guided evaluate condition also employ the pictorial analysis game. Participants in the guided evaluate condition however employed the evaluation of problem cases or construct and compare scenarios strategy in lieu of applying one of the other aforementioned strategies.

Results shown in Appendix N, indicate these participants employed no singular strategy to solve a given argumentative homework or interview problem. As Carson stated "how I solve the problem depends upon the problem" (Interview 3, April 1st). Similarly, Cayden stated, "I believe there are other ways to solve than just looking at formulas for a problem" (Interview 2, March 7th). Thus as results indicate, for a given problem participants in each case condition employed varying problem solving strategies ranging from application of intuition to formula-centered strategies to more conceptual application strategies. For instance, for Problems 2, 3, and 4 of the homework each case across the case conditions, there was no singular problem solving strategy employed by the participants. For Problem 2, 3, and 4 participants in each case condition employed physical mechanism, case reuse, and covariational reasoning. Participants in the control condition applied recursive concept testing, a strategy that was unique to that case. Participants in the guided construct condition on the other hand also applied hypothetical plug and chug, mapping meaning to mathematics, and qualitative concept application. Also participants in the guided evaluate condition employed qualitative concept application and compare and construct or evaluation of problem cases.

Additionally, within each case condition, there was no single strategy employed by all four participants. For homework Problem 1 however, covariational reasoning appeared to be a dominant strategy employed by each case condition. Although participants in the guided evaluate condition employed either evaluate problem cases or construct and compare strategies, these strategies were paired with the covariational reasoning strategy to solve the problem. The use of covariational reasoning may be attributed to the problem which lends itself to requiring the individual solver identifying and applying the definition of work (work equals force time distance) to the given problem information in order to predict the outcome. For homework Problem 5, qualitative concept application appears to be the dominant strategy employed by participants in each case condition. Although participants in the guided evaluate condition employed either evaluate problem cases or construct and compare strategies, these strategies were paired with the application of qualitative concept application. The use of qualitative concept application may be attributed to the fact that the problem lent itself to requiring the solver to identify and apply Newton's laws to the given problem information in order to predict the outcome.

Similar to the argumentative homework problems, results for the argumentative interview problems indicate that participants employed no singular strategy across or within each case condition. For instance, to solve Problem1 in the interviews, participants in each case employed physical mechanism game. However, participants in the control condition used other less sophisticated problem solving strategies such as recursive concept testing which was unique to this condition. Participants in the guided construct condition on the other hand also employed hypothetical plug-and-chug, a less sophisticated problem solving strategy that was unique to the condition. In addition to physical mechanism or hypothetical plug-and-chug, participants in the guided construct condition may employed covariational reasoning or qualitative concept application. Participants in the guided evaluate condition however employed pictorial analysis or qualitative conceptual analysis along with evaluating problem scenarios or construct and compare strategies. It should be noted that for each of the argumentative interview problems, participants in the control condition did not employ qualitative concept application, which is clearly a more sophisticated strategy and was utilized by participants in the guided construct and guided evaluate.

When comparing strategies that participants used to solve an argumentative homework problem to strategies used to solve an argumentative interview problem that is similar to the homework problem, there is a tendency for participants in each case to employ similar strategies for the problems. Specifically, Problem 1 of the interviews may be compared with Problem 2 of the homework due to the underlying concept being addressed. Likewise, Problem 2 of the interviews may be compared with Problem 3 of the homework and Problem 5 of the interviews may be compared with Problem 5 of the homework. To illustrate this point, results show that each participant in the control condition applied the strategy (physical mechanism or case reuse) they used to solve Problem 2 of the homework to Problem 1 of the interview. Additionally a participant in the guided construct condition – Brice – who applied hypothetical plug-and-chug for Problem 2 of the homework also applied the same strategy to Problem 1 of the interview. Likewise, participants in the guided construct who applied covariational reasoning, qualitative concept application, or physical mechanism for the homework problem applied the same strategy to the corresponding interview problem. Finally, participants in the guided evaluate employed similar strategies for corresponding problems.

The quantitative results of this study indicate significant differences for conceptual quality between the conditions for Problems 1, 2 and 4 of the homework (see Table 14). When examining which strategies each case employs for the above mentioned problems, participants in the control condition tended to employ limited, less sophisticated problem solving strategies. For example, in Problem 1 participants in the control condition predominantly employed covariational reasoning. Participants in the guided evaluate condition also employed covariational reasoning in addition to qualitative concept application along with evaluate problem cases and compare and construct strategies. For Problem 2, participants in the control condition utilized physical mechanism game, case reuse, and covariational reasoning. Participants in the guided construct also utilized covariational reasoning and case reuse in addition to hypothetical plug-and-chug and qualitative concept application. However, participants in the guided evaluate condition employed qualitative concept application or covariational reasoning along with evaluate problem cases and construct and compare strategies. Finally for Problem 4, participants in the control condition employed physical mechanism, recursive concept testing, covariational reasoning while participants in the guided construct condition employed physical mechanism and qualitative concept application. However, the guided evaluate condition employed physical mechanism game, covariational reasoning, and qualitative concept application along with construct and compare strategy for this problem. These differences could potentially be attributed to the ways in which participants utilized the hypothetical pseudo debate arguments provided in the guided evaluate condition.

The problem solving strategies employed by participants in each case condition can be influenced by how they solve the argumentative physics problems. Table 19 provides a cross case summary of the emergent themes pertaining to how participants in each case solved the argumentative physics problems. For instance, participants in both the control and guided evaluate conditions viewed intuition as a kind of evidence which could be employed in argumentation. Although participants in the guided construct condition did not view common sense or intuition as evidence, they may have limited themselves to offering a solution based upon intuition if they viewed the problem as a simple to solve problem. Hence, based upon views of evidence and justification of participants each condition's, they tended to employ the physical mechanism game, which was guided by their personal intuition.

Table 19

Emergent Themes by Each Condition Regarding How They Solve Argumentative Physics Problems

	Control	Guided Construct	Guided Evaluate
Driven by Views of Argumentation, Evidence, and Nature of Physics	X	X	X
Cues on Problem Features to Develop Solution Strategy	X	X	X
Influenced by Alternative Conceptions	X	X	X
Influenced by Personal Beliefs and Confidence to Solve and Justify	X	X	X
Usefulness of Argumentation Prompts		X	
Importance of Argumentation Prompts and Hypothetical Pseudo Arguments			X
Audience Limiting Justification		X	

RQ 4: Patterns of Strategies Prior to and During Argumentation Treatment

The sections below describe emergent patterns of problem solving strategies employed by participants in each case condition with varying levels of conceptual understanding (as measured by the FMCE) prior to instruction. Additionally, a cross-case section describes emergent patterns of problem solving strategies across cases used by participants with varying levels of conceptual understanding.

Patterns from Control Condition

Prior to solving the argumentative physics problems, all participants in the control condition described how they typically approached solving physics problems using recursive plug-and-chug or pictorial analysis strategies. Indeed, while solving an open-ended conceptual problem prior to receiving the argumentative physics problems, they employed hypothetical plug-and-chug, physical mechanism, case reuse, or pictorial analysis. Participants who were categorized as having a high level of conceptual understanding prior to instruction demonstrated various kinds of problem solving strategies while solving argumentative physics problem during the interviews. These strategies included physical mechanism, case reuse, recursive concept testing, pictorial analysis game, or covariational reasoning. Participants who were categorized as having a low level of conceptual understanding prior to instruction more often used the physical mechanism game and case reuse while solving problems during the interviews. While solving the argumentative homework physics problems, participants classified as having high level of prior conceptual understanding utilized more diverse problem solving strategies compared to participants classified as having low level of prior conceptual understanding. The latter group used physical mechanism, case reuse, and covariational reasoning, while the former group additionally used recursive concept testing and qualitative concept application, which are more sophisticated than the strategies only used by the low-level group.

Patterns for the Guided Construct Condition

Prior to solving the argumentative physics problems, participants who were classified as having a high level of conceptual understanding prior to instruction described how they typically approached solving physics problems. Their descriptions were consistent with using means-end or mapping meaning to mathematics strategies. While solving an open-ended conceptual problem prior to receiving the argumentative physics problems, these participants employed physical mechanism or pictorial analysis game. Alternatively, participants who were classified as having a low level of conceptual understanding prior to instruction described how they typically approach solving physics problems. Their descriptions were consistent with using the pictorial analysis game or recursive plug-and-chug strategies. While solving an open-ended conceptual problem prior to receiving the argumentative physics problems, these participants only the employed physical mechanism game.

Participants who were categorized as having a high level of conceptual understanding prior to instruction also demonstrated varying kinds of problem solving strategies while solving argumentative physics problem during the interviews. These strategies included physical mechanism, extreme case thought experiment/generate scenarios, covariational reasoning, and qualitative concept application. Participants who were categorized as having a low level of conceptual understanding prior to instruction more often demonstrated either the physical mechanism game or hypothetical plug-and-chug while solving problems during the interviews. Additionally, while solving the argumentative homework physics problems, participants who were classified as having a high level of prior understanding utilized more sophisticated problem solving strategies (e.g. mapping meaning to mathematics and qualitative concept application) compared to participants who were categorized as having a low level of prior conceptual understanding (physical mechanism, hypothetical plug-and-chug, and covariational reasoning).

Patterns for the Guided Evaluate Condition

Prior to solving the argumentative physics problems, participants who were classified as having a high level of conceptual understanding prior to instruction described how they typically approached solving physics problems. Their descriptions were consistent with using means-end or case reuse strategies. While solving an open-ended conceptual problem prior to receiving the argumentative physics problems, these participants employed only the physical mechanism game. Alternatively, participants who were classified as having a low level of conceptual understanding prior to instruction described how they typically approach solving physics problems. Their descriptions were consistent with using recursive plug-and-chug, means-end, or case reuse strategies. While solving an open-ended conceptual problem prior to receiving the argumentative physics problems, these participants employed physical mechanism game and case reuse.

Participants who were categorized as having a high level of conceptual understanding prior to instruction demonstrated varying kinds of problem solving strategies while solving argumentative physics problem during the interviews which included: pictorial analysis game, extreme case thought experiment, covariational reasoning, and qualitative concept application along with either evaluate problem cases or compare and construct. Participants who were categorized as having a low level of conceptual understanding prior to instruction more often demonstrated physical mechanism game and case reuse along with evaluate problem cases or compare and construct strategies while solving problems during the interviews. Additionally, while solving argumentative homework physics problems, participants who were classified as having a high level of prior understanding utilized more diverse and more sophisticated problem solving strategies (e.g. extreme case thought experiment and qualitative concept application along with either evaluate problem cases or construct and compare) compared to participants who were categorized as having a low level of prior conceptual understanding (physical mechanism and covariational reasoning along with either evaluate problem cases or construct and compare).

Cross-Case Patterns

Prior to receiving the argumentative physics problems, participants described how they solved typical physics problems. Their descriptions were consistent with less sophisticated, formula centered strategies. Indeed while solving an open-ended physics problem they predominantly employed strategies that relied upon their personal intuition. Patterns within each case revealed that participants who were classified as having a high level of conceptual understanding prior to instruction utilized more diverse problem solving strategies including more sophisticated strategies while solving argumentative problems. Participants who were classified as having a low level of conceptual understanding prior to instruction tended to utilize a limited number of strategies that were less sophisticated (e.g. physical mechanism, hypothetical plug-and-chug, case reuse, or covariational reasoning). The utilization of formula-centered strategies by this group could potentially be attributed to the kinds of problems they regularly solve in class or homework problems which are typically amenable to such strategies.

Summary

MANOVA results revealed that participants in the guided construct or guided evaluate condition constructed higher quality of written arguments compared to the control. However, there were no significant difference in argumentation quality between the guided construct and guided evaluate conditions. The guided construct and guided evaluate conditions had problem solutions of higher conceptual quality than the control. On one of five problems, the guided evaluate condition had a higher conceptual quality solutions than guided construct.

Results also indicated that differences in conditions may be influenced by problem context or topic. A multiple regression analysis revealed that condition and at times gender, and level of pre-conceptual understanding can predict argumentation and conceptual quality. MANOVA results also revealed gender differences with females constructing higher quality arguments compared to males. However, there was no significant interaction between gender and condition. Yet, results suggest that inclusion of open-ended response tasks may support females' conceptual quality in problem solutions. Pearson's product moment correlations revealed that there are positive, significant correlations between argumentation quality and conceptual quality for each condition. However, these correlations can be limited by context of the problem or level of conceptual understanding.

Findings from the qualitative phase revealed that participants are influenced by their views of argumentation, evidence, knowledge, justification, and nature of physics as they approach solving argumentative physics problems. Also participants in all three conditions relied upon surface features within the problem to develop a solution strategy opposed to identifying underlying physical principles. Alternative conceptions and personal beliefs or “my-side bias” also influence how undergraduates construct arguments, whether they offer counter-arguments, and they conceptual quality of the arguments. Offering of counter-arguments can also be influenced by participants’ ability to identify alternative approaches or solutions to a problem and ability to make assumption based on problem information. Participants in the guided construct condition did not view their argumentation prompts as useful however, participants in the guided evaluate condition recognized the importance of argumentative prompts and alternative argument statements in their problems. Findings also revealed that participants tend to apply formula-centered strategies or personal intuition while solving argumentative problems. However, results indicate that the argumentative problems for the guided construct and guided evaluate conditions expand participants’ solution strategies such as qualitative concept application or evaluation of problem cases to construct of solution.

CHAPTER FIVE

CONCLUSIONS AND IMPLICATIONS

This chapter includes a summary of the study and a summary of both quantitative and qualitative findings. The chapter then follows with conclusions of findings and assertions. Next, this chapter includes a discussion of conclusions in relation to literature to explain how this study contributes to the body of literature with implications for research and instruction. Finally, this chapter concludes with suggestions for future research.

Summary of Study

A review of literature suggested that scientific argumentation can enhance critical thinking, problem solving skills, ways of thinking, and can serve as a mechanism to aid in constructing and enhancing knowledge (Driver et al., 2000; Jonassen & Kim, 2010). Argumentation can be divided into two skills – skill of constructing an argument and skill of evaluating an argument. Effective argumentation requires interpretation and evaluation of evidence, assessing any potential alternatives, and addressing counter-positions to justify a solution (Driver et al., 2000; Jonassen et al., 2009). Numerous studies have reported that students have difficulties constructing arguments without appropriate scaffolds (Ge & Land, 2003; Jonassen et al., 2009; Rezitskya et al., 2001; Zeidler, 1997) and the relationship between argumentation and conceptual understanding is not quite clear (Dawson & Venville, 2009).

Physics education research has shown that students in introductory physics have limited problem solving abilities (Hsu et al., 2004). Students often apply formula-centered problem solving approaches, rarely reflect on the appropriateness or applicability of equations or physical concepts, or rarely consider alternative solutions (Leonard et al., 1996; Chi et al., 1981; Manson & Singh, 2010). Traditional physics instruction also seldom encourages students to justify or explain their solutions and use of equations and/or physical concepts (Dufresne et al., 2007). In physics education, it is recognized that interventions are needed to enhance students' problem solving skills and construction of qualitative explanations (Leonard et al., 1996). However, there are few such interventions that emphasize qualitative justification of solutions or argumentation.

The purpose of this study was to examine the effects of alternative forms of argumentation on students' solutions to physics problems across multiple topics in introductory calculus-based physics. Specifically, the goal was to compare written arguments generated by students who were prompted to construct or evaluate arguments and contrast each of those arguments with a control group. Additionally, the goal was to explore how students solve argumentative problems and what problem solving strategies they employed while solving. Hence, this study sought to investigate whether the integration of written argumentation into physics problems can help support students' abilities to solve problems and improve conceptual understanding.

In this study, word problems similar to those in the PbI (McDermott, 1996) curriculum were designed to scaffold students' construction and evaluation of arguments and compared to a traditional question format. To examine the effects of alternative forms of argumentation on students' solutions, two types of argumentation tasks were utilized – construct an argument and evaluate alternative arguments. The evaluate an argument condition was utilized because the nature of the task is similar to McDermott's (1996) PbI hypothetical pseudo debate tasks. Argumentative question prompts adapted from Jonassen et al. (2009) and Manson and Scirica (2006) were used to scaffold the construct and evaluate tasks. The control condition was only provided "explain your reasoning" prompt which is similar to the question statement used in the PbI curriculum.

In completing this study, the researcher utilized a theoretical framework based on TAP (Toulmin, 1958) to describe argumentation and epistemic games (Tuminaro & Redish, 2007) to describe participants' problem solving strategies. TAP is commonly used in argumentation research to analyze the structure of arguments but not the quality of the content. Toulmin identifies six elements that undergird an argument: claim, data, warrant, backing, qualifiers, and rebuttals. The strength of an argument is primarily based on the presence or absence of specific combinations of these elements (Sampson & Clark, 2008). Specifically, a stronger argument would consist of all elements of an argument.

Epistemic games provide a model to describe activities employed by students while solving problems. By identifying games employed by students during problem solving, one can deconstruct students' expectation about how to approach problem solving in physics (Tuminaro & Redish, 2007). Tuminaro (2004) and Tuminaro and Redish (2007) identified six epistemic games employed by students while solving open-ended and algebraic physics problems: (i) mapping meaning to mathematics, (ii) mapping mathematics to meaning, (iii) physical mechanism game, (iv) pictorial analysis game, (v) recursive plug-and-chug, and (vi) transliteration to mathematics or case reuse. Tuminaro and Redish emphasized that possible problem solving approaches in physics are not limited to the six aforementioned games. Thus new games may emerge while solving alternative forms of physics problems.

To address the purpose of this study, a two-phase concurrent mixed methods design (Creswell & Plano Clark, 2007) was employed which incorporated quantitative and qualitative phases. For the quantitative phase, the FMCE (Thornton & Sokokoff, 1998) was used to assess students' prior understandings before instruction and results were used to assign participants to control, guided construct, or guided evaluate conditions. Additional quantitative data were collected from students' responses to five argumentative homework questions from within their respective condition. Responses were scored using two scoring rubrics. One was adapted from Sadler and Fowler (2006) for argumentation quality. The other was created to score the conceptual quality based on the correctness of the reasoning in the response. The quantitative results involved scores based on each rubric for 210 students (42 females, 168 males) on relevant homework problems. The analysis consisted of descriptive statistics and a MANOVA was used to determine if conditions and gender have a significant effect on students' argumentation quality and conceptual quality of students' solutions. A Pearson's product moment correlation was also performed to analyze the relationship of conceptual quality and argumentation quality of responses for each of the conditions. Finally, a multiple regression was performed for FMCE scores and gender on scores for argumentation quality and conceptual quality.

To understand how students solve argumentative physics problems and what problem solving strategies they may have utilized while solving such problems, a multiple case study design was implemented (Yin, 2008). In this study, via stratified random sampling, four participants from each of the guided construct, guided evaluate, and control conditions were selected. Each condition constituted a case. Performance on the FMCE served as a basis for participant selection. For each condition, two participants were selected as having: an above average score on the FMCE and a below average score on the FMCE. The multiple-case study design offered emergent themes and a cross-case analysis of emergent patterns related to how students approach solving argumentative physics problems and what problem solving strategies they utilized.

For the qualitative phase, three audio-recorded interview sessions were conducted with each participant. During the interviews, a semi-structured interview protocol was used to facilitate participants' discussion of how they solved previous argumentative homework problems. Additionally, the interviews included a think-aloud problem solving session. During the think-aloud session, students solved argumentative problems related to topics which they completed in their homework. The primary data sources were the transcribed interview sessions and artifacts such as written responses generated during the interview and completed homework.

Analysis for the qualitative phase consisted of organizing all multi-source data into a case record (Patton, 2002). The researcher then applied an open coding process, using descriptive and explanatory codes, to each interview and artifact. Codes were then collapsed to reduce redundancies and combined similar codes. Next, themes were developed from a refined code list for each case. Analysis of codes and tentative themes revealed that the emergent problem solving strategies employed by each participant closely aligned with Tuminaro and Redish's (2007) framework of epistemic games. Thus, the framework for epistemic games was utilized for further analysis of themes concerning participants' problem solving strategies. Once themes emerged for a case, the researcher investigated the data closely for any evidence refuting the emergent theme (Cresswell, 2007). When case profiles were established, a cross-case analysis was performed to determine similarities and differences between the conditions (Yin, 2008). A table was constructed to compare themes across and within case to identify emergent patterns (Cresswell, 2007; Miles & Huberman, 1994). Assertions were then generated by comparing findings from each case against theoretical assertions based upon literature and comparing emergent themes (Yin, 2008).

Summary of Findings

The study's research questions were answered using quantitative and qualitative data. The following sections examine the results of this study for each research question. The final section describes connections between quantitative and qualitative results.

Quantitative Results

Research question 1: Is there a difference between guided construct, guided evaluate and control conditions and/or male and female students on their argumentation quality and/or quality of problem solutions? Results of the MANOVA revealed statistically significant differences among the three conditions and gender for each of the five problems. These results indicated significant differences between conditions for argumentation and conceptual quality scores. Additionally, there were differences between gender for argumentation and conceptual quality scores. Univariate ANOVAs revealed significant differences with large effects among the three conditions on the argumentation scores for the five problems. Also there were significant differences with small effects on the conceptual scores for Problem 1 (work and kinetic energy) and 4 (momentum and impulse). Univariate ANOVAs also reveal significant differences with small effects between gender, with females outperforming males on their argumentation scores for Problems 1 (work and kinetic energy), 2 (energy conservation), 3 (momentum conservation), and 4 (momentum and impulse). Also there were significant differences with small effect, with females outperforming males on conceptual scores for Problem 1 (work and kinetic energy).

A follow-up Tukey's HSD analysis revealed that guided construct and guided evaluate conditions were statically greater then the control condition for argumentation quality of the five problems. There were no significant differences between guided construct and guided evaluate argumentation scores for each of the five problems. For conceptual quality, Tukey's HSD analysis revealed that the guided evaluate condition was statistically greater than the control condition for Problems 1 (work and kinetic energy), 2 (energy conservation), and 4 (momentum and impulse).The guided construct condition yielded a statistically greater score compared to the control for Problem 2 (energy conservation). However there were no significant differences between guided construct and control for Problems 1 (work and kinetic energy) and 4 (momentum and impulse). There were no significant differences between guided construct and guided evaluate for Problem 2 (energy conservation). Yet, for Problem 4 (momentum and impulse), the guided evaluate condition yielded a statistically greater score than guided construct although there were no significant differences between guided construct and control conditions. There were no significant differences between the conditions for Problems 3 (momentum conservation) and 5 (gravitation – Newton's III law).

Research question 2: Is there an interaction between gender, guided construct, guided evaluate and control conditions regarding argumentation quality and/or quality of problem solutions? Means for argumentation and conceptual quality scores reveal that female participants tended to yield higher scores compared to males across the conditions for each of the five problems. Results of the MANOVA revealed no statistically significant interaction of gender and condition regarding argumentation and conceptual quality scores.

Research question 3: Is there a relationship between the quality of students' solutions to physics problems and argumentation quality for the guided construct, guided evaluate, and control conditions? Results of the Pearson product moment correlation revealed that there were small to moderate, positive significant correlations between argumentation quality and conceptual quality. Specifically, there were significant correlations for the control condition for Problems 1 (work and kinetic energy), 2 (energy conservation), 4 (momentum and impulse), and 5 (gravitation – Newton's III law). For guided construct, there were significant correlations for Problems 4 (momentum and impulse) and 5 (gravitation – Newton's III law). Also for guided evaluate, there were significant correlations for Problems 1 (work and kinetic energy), 4 (momentum and impulse), and 5 (gravitation – Newton's III law). There were no significant correlations for Problem 3 (momentum conservation) for each of the conditions.

Research question 4: Is there a relationship between students' pre-conceptual understanding and/or gender and quality of problem solution and/or argumentation quality? Results of the multiple regression revealed that condition significantly predicted argumentation quality for each of the five problems. For Problems 1 (work and kinetic energy), 3 (momentum conservation), and 4 (momentum and impulse), gender also significantly predicted argumentation quality. In addition to condition and gender, the FMCE also predicted argumentation quality for Problem 1 (work and kinetic energy), but for Problem 5 (gravitation - Newton's III law) only condition and FMCE predicted argumentation quality. For conceptual quality on the other hand, condition, gender, and FMCE predicted scores for Problems 1 (work and kinetic energy) and 2 (energy conservation). However for Problem 4 (momentum and impulse), only condition predicted conceptual quality and for Problem 5 (gravitation - Newton's III law) only FMCE predicted conceptual quality.

Qualitative Results

Research question 1: How do undergraduate introductory physics students solve physics problems supporting alternative forms of argumentation? Results reveal, in total, eight emergent themes pertaining to how participants solve problems supporting alternative forms of argumentation. Four central themes were shared by each of the conditions: driven by views of argumentation, evidence, knowledge, and nature of physics; cues on problems features to develop solution strategy; influenced by alterative conceptions; and influenced by personal beliefs and confidence to solve and justify.

How participants' perceived what argumentation is or consist of, what is viewed as evidence, and views of knowledge, truth, and justification in physics can influence how participants respond to the tasks. There is a tendency for participants to describe argumentation as consisting of offering a position with evidence and someone may disagree. Yet, participants do not mention the inclusion of rebuttal in argumentation. For the control and guided construct conditions, there is a tendency to view intuition or common-sense as reasonable evidence. However, each condition also views equations, physical concepts or laws, experimentation or demonstrations, observations, or problem information as evidence. Yet, equations are considered more convince evidence since they “provide right answers.” Among the participants there is a perception that an argument in physics is true if it is justified with authoritative knowledge, observations or real-world experience, or application of a concept or equation that seems relevant. The perception of relevance for an equation or concept is based upon features or variables extracted from the problem and matched with variables in an equation. Students’ reliance upon equations to solve physics problems are, in part, contributed to the perception that physics is about using equations to solve for numerical answers. Hence there is a tendency to approach solving argumentative problems with formula-centered methods.

While solving argumentative physics problems, participants cue on surface features, such as keywords or facts, within a problem statement or picture as a means to extract problem information. Based on surface information of the problem, participants then attempt to identify physical concepts or equations to apply to the problem to construct an argument. Participants also group or classify physics problems (e.g. a gravitation problem) in which they refer to specific concepts they have associated to that group of problems.

Alternative conceptions can also influence how participants solve argumentative physics problems and the conceptual quality of the proposed argument. Participants’ cues on problem features may at times facilitate the application of alternative conceptions to the problem. Specifically, by relying on surface features of a problem opposed to the underlying physical principles, they may miss-identify an appropriately physical concept or equation. Additionally, participants’ deeply rooted misconceptions what concept or equation is identified and/or how that concept or equation is applied. For instance, they may identify an appropriate concept but inappropriately applies the concept to the problem.

Participants' personal beliefs or "my-side" bias also tends to influence the quality of the argument or how they solve argumentative problems. Specifically, personal beliefs can influence whether or not they consider counter-arguments within their own written arguments. Often participants viewed that if a counter-argument to their solution was identified it would be because the opposing individual lacks an appropriate understanding of physics. If they do consider counter-arguments, their personal beliefs may influence how they identify or evaluate the proposed counter-argument. Often participants evaluated an identified counter-argument by restating their own solution and reasons why it is correct. Confidence about their understanding of physics and the appropriateness of their written solution can also influence the manner in which they solve and the conceptual quality of the constructed argument.

Additionally, there were four themes unique to guided construct and guided evaluate conditions. Both guided construct and guided evaluate shared variability in offering counter-arguments. Here, ascertain possible counter-arguments can be influenced an ability to identify how someone could approach a problem differently or an alternative solution someone could logically obtain. The ability to identify alternative solutions is not only limited to their personal beliefs but identifying and choosing from possible outcome scenarios, identifying varying assumptions based upon the problem information, and their understanding of physics.

Usefulness of argumentation prompts and audience limiting justification was unique to guided construct. Participants in the guided construct condition did not express that the argumentative prompts were helpful. The only prompt statement they viewed as important is making sure to offer evidence to justify their solution. This perhaps connects with the next theme in which participants wrote their argument to whom they perceived is the audience. They assume the audience (e.g. the homework grader) understands physics and can determine whether their solution is physically right or wrong and therefore they do not need to provide elaborated justification.

Finally, the importance of argumentation prompts and hypothetical pseudo statements were unique to the guided evaluate condition. Unlike the guided construct condition, participants in the guided evaluate condition viewed the argumentative prompts as helpful for reflecting upon and further supporting their solution. Additionally, the prompts provided a means to organize their writing which made it easier to construct a qualitative solution. Participants also expressed that the pseudo debate arguments were useful if they were in doubt about how to approach solving the problem. They would evaluate the arguments for keywords or differences for clues as to how to solve the problem. There were perceptions that the pseudo debate arguments were not always useful because, through the participants' experience with the problems, they recognized the arguments presented flaws in their answers or reasoning. Therefore at times, participants found it easier to solve a problem by first developing their own solution and then compare their solution to the pseudo arguments. The participants acknowledged that the hypothetical pseudo debate statements at times can serve as an easy identifiable possible counter-argument to address.

Research question 2: What problem solving strategies do students use to solve problems incorporating construction or evaluation of arguments in physics? Tuminaro and Redish (2007) describe six problem solving strategies that students may employ while solving algebraic and conceptual physics problems in a second-semester algebra physics course. In this study, results indicate an alignment with strategies identified by Tuminaro and Redish (2007) such as physical mechanism game, recursive plug-and-chug, case reuse or transliteration to mathematics, pictorial analysis game, and mapping meaning to mathematics. Results of this study also indicate six additional strategies that students may employ with solving varying forms of argumentation problem in physics. These strategies are recursive concept testing, extreme case thought experiment/generating scenarios, covariational reasoning, qualitative concept application, evaluation of problem scenarios, and constructing and comparing solutions.

Qualitative results of this study revealed, in total, 11 problem solving strategies employed while solving argumentative physics problems. Each of the three conditions employed physical mechanism game, case reuse, covariational reasoning, and qualitative concept application strategies. Other strategies unique to the control condition include recursive concept testing and pictorial analysis game. Additional strategies unique to the guided construct condition include recursive/hypothetical plug-and-chug, extreme case thought experiment, and mapping meaning to mathematics. Strategies unique to the guided evaluate condition that were also employed include extreme case thought experiment, pictorial analysis game, evaluation of problem cases, and construct and compare solutions.

Research question 3: In what ways are students' problem solving strategies for varying argumentation problems formats similar to or differ from traditional "explain your reasoning" problem formats? Results of this study indicated that each of the three conditions (control, guided construct and guided evaluate) shared similar and unique problem solving strategies. However, the frequency of each strategy employed within each condition varied. For instance, results showed that participants in each case condition employed intuitive or formula-centered strategies. However, participants in the control condition more often tended to utilize personal intuition or formula-centered strategies compared to participants in the other conditions. In fact, compared to guided construct and guided evaluate, the control condition more often employed less sophisticated problem solving strategies (e.g. physical mechanism or covariational reasoning) while solving both homework and interview argumentative problems. Results also suggest that participants within and across cases employed no single strategy while solving a given argumentative problem. Hence, problem solving strategies employed by participants in each case condition could potentially be influenced by how they approach solving argumentative physics problems among other factors that are not of the scope of this study.

Research question 4: What patterns emerge for problem solving strategies from students who have varying levels of conceptual understandings prior to and during the argumentation treatment? All participants across the three conditions described how they typically approached solving physics problem. Strategies they described tended to be formula-centered, intuitive, or relied on the use of diagrams (e.g. recursive plug-and-chug, means end, and pictorial analysis game). Indeed while solving an open-ended conceptual problem that was intended to assess their initial problem solving strategies prior to receiving the argumentative physics problems, nearly all participants employed the physical mechanism game. Hence, participants' descriptions and initially employed strategies across the cases were consistent with less sophisticated, formula centered or intuitive strategies.

While solving homework as well as interview argumentative physics problems, participants' range of strategies increased and varied for those who were categorized as a high level or low level of conceptual understanding prior to instruction. For instance, in the control condition, participants who were categorized as a high level of understanding employed a wider range of strategies than the low understanding group which included: physical mechanism, case reuse, recursive concept testing, pictorial analysis game, covariational reasoning, and qualitative concept testing. However, participants who were categorized as low understanding often employed physical mechanism game, case reuse, and covariational reasoning. Although both high and low conceptual understanding participants across the cases increased in the range of strategies compared to the initial strategies utilized, those who were categorized as high demonstrated a wider range compared to those who were categorized as low understanding.

Connections between Quantitative and Qualitative Results

Qualitative results of the emergent themes of participants' approaches to solving argumentative physics problems can explain the quantitative results that show differences between the three conditions in the argumentation and conceptual quality scores. Specifically, thematic differences between the conditions in participants' approaches to solving argumentative physics problems can explain why participants in the guided construct and guided evaluate conditions demonstrated statistically significantly higher argumentation quality and conceptual quality scores than participants in the control condition.

One thematic difference observed in the qualitative study between the conditions is in the perceived usefulness and importance of argumentation prompts, with participants in guided construct perceiving the argumentative prompts as not being useful, while the guided evaluate condition perceiving the prompts as being useful. Participants in the guided evaluate condition stated that the prompts helped organize their writing and be able to reflect upon their solution. Although those in the guided construct condition did not view the argumentative prompts as useful; they still appeared to have utilized those prompts while constructing a response both for the argumentative homework problems and interview problems. Use of the prompts can potentially be attributed to another thematic difference in which participants in the guided construct condition wrote to the audience (e.g. the homework grader). Hence, the utilization of argumentative prompts for the guided construct and guided evaluate conditions does influence argumentation performance compared to the control condition. Participants in the guided evaluate condition also stated that the hypothetical pseudo debate statements offered clues or keys words which helped them develop a solution strategy. Hence the hypothetical pseudo debate statements for the guided evaluate condition can have an influence on conceptual performance compared to the guided construct and control conditions.

Although participants in all conditions demonstrated the theme of being influenced by personal beliefs and confidence in their ability to solve and justify the problems, the participants in the control condition more often exhibited my-side bias in their responses compared to the guided construct or guided evaluate conditions. Specifically, those in the control condition were unwilling to consider alternative solutions to a problem or were unaware that they should do so. Hence the control conditions' argument quality is significantly less compared to guided construct and guided evaluate condition.

Qualitative results of the emergent themes of participants' problem solving strategies applied toward argumentative physics problems can also explain the quantitative results that show differences between the three conditions in the argumentation and conceptual quality scores. Specifically, thematic differences between the conditions in participants' approaches to solving argumentative physics problems can explain why participants in the guided construct and guided evaluate conditions demonstrated statistically significantly higher argumentation quality than participants in the control condition. Further, these thematic differences explain why the conceptual quality of responses from participants in the guided evaluate condition were statistically significantly greater to those in the guided construct condition which in turn were greater to those in the control condition.

A general trend in the qualitative study observed across all emergent themes is that participants in the control condition used more intuitive and less sophisticated problem solving strategies than participants in either the guided construct and guided evaluate conditions. One thematic difference observed in the qualitative study between the conditions is in the use of extreme case thought experiments. Participants in both the guided construct and guided evaluate condition tended to use this strategy where as participants in the control condition did not do so. Another thematic difference was that participants in the guided construct condition used the mapping meaning to mathematics strategy that is more sophisticated than more plug-and-chug approaches used by participants in the control condition. Further, two other thematic differences were in the use of evaluation of problem scenarios strategy as well as constructing and comparing solutions strategy. Both of these approaches were demonstrated by participants in the guided evaluate condition, but not by participants in the guided construct or control conditions.

Conclusions and Assertions

The following section offers conclusion of results and assertions.

Conclusion 1

Results of this study concerning argumentation quality for the five problems suggest that guided construct and guided evaluate argumentation tasks produced higher quality of arguments compared to a typical problem statements ("explain your reasoning") used in the PbI and other curriculum. Also this study indicates that there is no significant difference between guided construct and guided evaluate tasks for quality of arguments.

Assertion 1

The "explain your reasoning" problem statement as used in the PbI curriculum may not produce higher argumentation level such as considering possible counter-arguments and rebuttals, without appropriate scaffolding to do so. The format of the argumentation problem (construct vs. evaluate) does not make a difference to the quality of arguments generated. However, argument quality can be limited by context of the problem.

Conclusion 2

MANOVA results indicated that females compose stronger arguments compared to males, however there was little impact on conceptual quality, with the exception of

Problem 1 (work and kinetic energy) on which females outperformed males. However, results indicate there was no significant interaction between gender and condition regarding argumentation and conceptual quality scores. Additionally, the multiple regression results reveal that condition, gender, and FMCE scores can significantly predict argumentation and conceptual quality. However, the influence of these factors appear to be context or topic dependent.

Assertion 2

Inclusion of open-ended response tasks in which students construct arguments can benefit female students for both argumentation skill development and conceptual understanding. Yet, the use of such tasks to support conceptual understanding can be limited by the context of the problem or other factors such as condition or level of prior conceptual understanding as measured by the FMCE. However, the kinds of argumentative prompts employed may have little impact on argumentative performance by females alone but as mentioned in Conclusion 1 can improve overall argument quality for all students.

Conclusion 3

Results of the Pearson's product correlation revealed significant, positive linear relationships between argumentation quality and conceptual quality. However, these relationships appear to be dependent upon the problem/context. For each of the three conditions, there were significant correlations for homework Problems 4 (momentum and impulse) and 5 (gravitation – Newton's III law). Upon examination of means, each condition's performance on Problems 4 and 5 was less compared to other problems. Additionally, except for Problem 3 (momentum conservation) and unlike guided construct and guided evaluate, the control condition revealed positive correlations for each problem. Again, upon examination of the means, scores for the control condition is lower compared to the means for the other conditions. Specifically, results indicate that if the conceptual quality of an argument is low then the argumentation quality is likely to be low.

Assertion 3

There is a relationship between argumentation quality and conceptual quality of a solution. However, relationships between argumentation and conceptual quality appear to be dependent upon context of the problem. If the conceptual quality of a problem solution is low then the argumentation quality is likely to be low, for either condition. As the conceptual quality of a problem solution increases, results reveal more variability in argumentation quality. Thus correlations between argumentation and conceptual scores become less likely. The results appear to suggest that there is a conceptual quality cutoff score in which more variability in argumentation scores are reached. Solutions with a conceptual quality score above this cutoff, tend to display a greater variation in argumentation quality compared to solutions below this conceptual quality cut-off score. This observation warrants further investigation.

Assertion 4

Results of the qualitative phase of this study suggest that argumentation quality can be limited by how students approach solving argumentative physics problems. These limitations include: students' views of argumentation, evidence, knowledge, and nature of physics; problem features they cue on to develop solution strategies; alternative conceptions; and personal beliefs and confidence to solve the problem and justify their solutions. Additional themes unique to guided construct and guided evaluate conditions include variability in offering counter-arguments, usefulness of argumentation prompts, importance of argumentation prompts and hypothetical pseudo statements, and audience limiting justification. Hence, students' views and approaches to how they solve argumentative physics problems can influence the quality of arguments they construct. These limitations include, but are not limited to students' views of argumentation, evidence, knowledge, and nature of physics; problem features that they cue on to develop solution strategies; alternative conceptions; and personal beliefs and confidence to solve and justify. Additional themes unique to guided construct and guided evaluate conditions include: variability in offering counter-arguments, usefulness of argumentation prompts, importance of argumentation prompts and hypothetical pseudo statements, and audience limiting justification.

Assertion 5

Participants in each of the three conditions employed a wide range of problem solving strategies while solving both homework and interview argumentative physics problems. However, participants who are classified as having high conceptual understanding prior to instruction in the guided construct and guided evaluate conditions can often employ more sophisticated problem solving strategies (e.g. qualitative concept application).

Results of this study indicate an alignment with strategies identified by Tuminaro and Redish (2007) such as physical mechanism game, recursive plug-and-chug, case reuse or transliteration to mathematics, pictorial analysis game, and mapping meaning to mathematics. Results of this study also indicate an additional problem solving strategy identified in literature – covariational reasoning (Hung & Jonassen, 2006). Additionally, results of this study suggest five additional strategies, not identified in literature, which students may employ with solving varying forms of argumentation problem in physics. These strategies are recursive concept testing, extreme case thought experiment/generating scenarios, qualitative concept application, evaluation of problem scenarios, and constructing and comparing solutions. Thus, problems supporting argumentation in physics may enhance students' problem solving skills. Although students may refer to formula-centered strategies while solving, argumentative problems can enhance the range of problem solving strategies that can be employed. However, the problem solving strategy an individual employs for a given problem can be influenced by the epistemological beliefs about problem solving in physics, views of argumentation and evidence, context of the problem, and other factors.

Discussion

Research by Cho and Jonassen (2002) show that scaffolds, including question prompts, support argumentation skills. Similar to Jonassen et al.'s (2009) results, findings of this study concerning argumentation quality for the five problems suggests that using construct and evaluate alternative argument tasks with prompts produce higher argumentation qualities. In fact, typical problem statements ("explain your reasoning") used in the PbI and other curriculum tend not to produce higher argumentation quality than if students are appropriately guided to provide rationale. Hence, the open-ended and hypothetical student debate problems as used in the PbI curriculum may not produce higher argumentation level such as considering possible counter-arguments and rebuttals, without appropriate scaffolding. Also similar to Jonassen et al.'s (2009) results, this study found that there is no significant difference between guided construct and guided evaluate conditions for stronger argument structures. Similar to Newton et al. (1999) we find that the strength of an argument can depend upon the context and nature of the task. Hence, argument quality can be limited by the context of the problem.

Results suggest that the guided evaluate condition may have a greater impact on conceptual quality. For Problems 1, 2, and 4, the guided evaluate condition outperformed the control condition and for Problem 4 (momentum and impulse) the guided evaluate condition outperformed the guided construct condition. Only for Problem 2 (energy conservation) did the guided construct condition outperform the control condition. Yet for Problem 2 (energy conservation), there was no significant difference between guided construct and guided evaluate conditions. Thus, the use of a hypothetical student debate problem used in PbI paired with argumentative prompts can produce higher conceptual quality justification used in arguments. These results seem to suggest that differences due to problem format may be influenced by problem context/topic.

With appropriate scaffolding, Bell and Linn (2007) found female students composing stronger arguments than males. Results of this study also indicate that female students tend to construct a higher quality argument compared to males. These results are unlike others which find no strong gender differences in argumentation (Kuhn, 1991). However, results of this study revealed no significant interaction between gender and condition regarding argumentation and conceptual quality scores. Thus, the different types of argumentative prompts employed in this study did not impact argumentation performance by females and males differently. Similar to Bell and Linn (2007), results of this study appear to be consistent with findings that females write more coherent essays than males (Hyde & Linn, 1988). Indeed prior studies reveal that females outperform males on short answer and essay items (Gipps & Murphy, 1994).

Similar to Bell and Linn's (2000) results, although females made more elaborated, higher quality arguments, there was little impact on conceptual quality. Males and females' responses demonstrated equivalent levels of conceptual quality for a given problem. This is with the exception of Problem 1 (work and kinetic energy) in which females conceptually outperformed the males. Hence, argument and conceptual quality can be limited by the context of the problem. This limitation can potentially be influenced by several factors including students' conceptual understanding or comfort level with a topic, personality, culture, and situational dynamics (Goldsmith & Fulfs, 1999). Similar to considerations offered by Goldsmith and Fulfs (1999), multiple regression results reveal that condition and at times, gender and FMCE performance can significantly predict argumentation and conceptual quality. Hence, prior conceptual understanding may be a factor influencing performance.

Prior studies reveal that argumentation may be influenced by conceptual understanding (Dawson & Venville, 2010). Von Aufschnaiter et al. (2008) suggest that argumentation quality is limited by students' familiarity or understanding of a topic. Similarly, Schwartz et al. (2003) found that lack of familiarity with a topic can prevent students from producing an argument with a complex structure (e.g. considering alternative viewpoints) and with acceptable justification. Alternatively, Sadler and Fowler (2006) propose that there is no clear linear relationship between argumentation and conceptual understanding. Instead they propose a non-linear relationship yielding three theoretical thresholds (Sadler & Donnelly, 2006; Sadler & Fowler, 2006). Hence as

Dawson and Venville (2010) emphasized, the relationship between argumentation and conceptual understanding is not straightforward.

Similar to results of von Aufschnaiter et al. (2008) and Zohar and Nemet (2002), results of this study suggest positive, significant linear relationships between argumentation quality and conceptual quality. However, these relationships appear to be dependent upon the problem/context. For each of the three conditions, there were significant correlations for Problems 4 and 5. Upon examination of means, the scores in each condition was less less than to the scores other problems in the corresponding conditions. Additionally, except for Problem 3 (momentum conservation) and unlike guided construct and guided evaluate, the control condition revealed positive correlations for each problem. Again, upon examination of the means, scores for the control condition are lower than the other conditions. Specifically, results indicate that if the conceptual quality of an argument is low then the argumentation quality is likely to be low. Hence, results appear to suggest that there is a cut-off in conceptual quality scores. Above this cut-off there is a greater variation in argumentation scores than below the cut-off.

Argument quality can be limited by the context of the problem (Newton et al., 1999). This limitation can potentially be influenced by factors (including those that emerged from the interviews) such as students' conceptual understanding or comfort level with a topic, their focus on redundant features of a problem as opposed to underlying concepts. Other factors include an application of what students consider to be "good" evidence, as well personality, culture, and situational dynamics (Goldsmith & Fulfs, 1999). Additionally, as Tuminaro and Redish (2007) suggest, expectations or views about problem solving in physics may influence the kind of problem solving strategy they choose to employ.

This study revealed that how students solve argumentative physics problems can be influenced by, but not limited to students' views of argumentation, evidence, knowledge, and nature of physics; cues on problem features to develop solution strategies; alternative conceptions; and personal beliefs and confidence to solve and justify. Additional themes unique to guided construct and guided evaluate conditions include variability in offering counter-arguments, usefulness of argumentation prompts, importance of argumentation prompts and hypothetical pseudo statements, and audience limiting justification.

Physics education research has shown that students in introductory physics have limited problem solving abilities (Hsu et al., 2004). They often apply formula-centered problem solving approaches, rarely reflect on the appropriateness or applicability of equations or physical concepts, or rarely consider alternative solutions (Leonard et al., 1996; Chi et al., 1981; Mason & Singh, 2010). Results of this study also reveal that participants may utilize formula-centered or intuitive strategies to solve argumentative physics problems. Yet, participants in each of the three conditions employed a wider range of problem solving strategies while solving both homework and interview argumentative physics problems. However, participants who are classified as having high conceptual understanding prior to instruction in the guided construct and guided evaluate conditions can often employ more sophisticated problem solving strategies (e.g. qualitative concept application). Hence, problems supporting argumentation in physics may enhance students' problem solving skills.

Tuminaro and Redish (2007) describe six problem solving strategies that students may employ while solving algebraic and conceptual physics problems in a second-semester algebra physics course. In this study, results indicate an alignment with strategies identified by Tuminaro and Redish (2007) such as physical mechanism game, recursive plug-and-chug, case reuse or transliteration to mathematics, pictorial analysis game, and mapping meaning to mathematics. Results of this study also indicate an additional problem solving strategy identified in literature: covariational reasoning (Hung & Jonassen, 2006). Additionally, results of this study suggest five additional strategies, not identified in literature, which students may employ with solving varying forms of argumentation problem in physics. These strategies are recursive concept testing, extreme case thought experiment/generating scenarios, qualitative concept application, evaluation of problem scenarios, and constructing and comparing solutions. All conditions utilized qualitative concept application however, recursive concept testing was unique to the control condition and similarly, evaluation of problem scenarios and comparing solutions was unique to the guided evaluate condition. Also extreme case thought experiment/generating scenarios was unique to both the guided construct and guided evaluate conditions.

Implications

Findings of this study suggest that incorporating physics problems supporting argumentation may be useful in enhancing students' problem solving skills. Additionally, incorporating open-ended, conceptual physics problems such as the argumentative problems utilized in this study may benefit female students' performance, which is especially important since it runs contrary to prior research that has shown that males outperform females in physics. The findings also show that while incorporating argumentative problems, especially those similar to PbI's hypothetical pseudo debate tasks may support students' conceptual understanding, the incorporation of scaffolds, such as question prompts, with the problem statement can yield higher argumentation quality and conceptual quality of problem solutions.

Argumentation tasks presented in this study may have the potential to lend themselves to instructional adoption as they have a lower barrier for course implementation because they need simple, albeit careful redesign of traditional physics problems. Findings of this study provide implications for redesign of traditional physics problems to support argumentation. As for the nature of the argumentative task -- construct or evaluate an argument -- results indicate that the nature of the task does not make a significant difference for argumentation quality. However, results do indicate that perhaps the evaluate task may offer a greater impact on conceptual quality. Additionally, designers should consider how structured the argumentative problems should be. Problems that are too well-structured may present challenges in encouraging students to construct arguments when there is little to argue about. Also, such argumentative problems are different in design compared to structured traditional physics problem which students typically receive. Hence, while designing and implementing such problems, educators should consider students' views about physics, argumentation, and evidence and their epistemological stances. Finally, it may not be adequate to embed argumentative problems within traditional physics problems, but the incorporation of argumentation should be a part of the course goals.

Future Research

Based on results and discussion of this study, the researcher suggests the following for future research concerning argumentation in physics. The first two concern the factors affecting argumentation. The next two are concerned with the contexts in which argumentation can be investigated. The next three are concerned with the types of of argumentation tasks that can be used. Finally, the last one is concerned with the design of prompts used in argumentation tasks.

1. There has been limited research concerning the interplay between argumentation, conceptual understanding, and epistemological beliefs. Future research should investigate the interplay between these factors, specifically in the context of physics problem solving.
2. Results of this study revealed gender differences, indicating that females outperformed males on argumentation tasks. This result is particularly interesting given that most of the research in physics education thus far has shown that males outperform females on conceptual assessments. However, research concerning gender differences in argumentation is presently limited (Nussbaum & Schraw, 2007). This is particularly true with regard to physics. This warrants additional research to investigate gender differences on argumentation tasks in physics.
3. Presently there is limited research regarding argumentation in physics. In this study the research investigated written argumentation. Additionally research should consider the implementation of dialogic argumentation in small group setting such as during recitation sessions.
4. In this study, argumentative physics problems served as both the intervention and assessment of argumentation skills. Future research should consider transfer effects of

argumentation skill development. Specifically, are students who practice solving argumentative tasks able to transfer their argumentation skill to immediate and delayed transfer tasks?

5. This study investigated the use of argumentation in the context of conceptual physics problems. These problems were in a sense atypical of end-of-chapter homework or exams problems used in an algebra- or calculus-based physics course, in that they did not require the use of equations or quantitative reasoning. For argumentation task design purposes, future research should consider what physics instructors and students consider to be “good” physics problems, and then investigate the use of strategies to argumentize these problems. Use of these kinds of typical physics problems will further lower the barrier for the use of argumentation in a typical introductory physics class.
6. Research on students’ argumentation and conceptual quality need not be limited to the use of word problems. In fact, there has been extensive research in physics education on the use of multiple representations. However, such research has focused on quantitative problems that students typically tend to solve using intuitive or plug-and-chug strategies. The findings of this study show that problems with prompts scaffolding argumentation can expand the repertoire of students’ problem solving strategies. Thus, it would be worthwhile to investigate argumentative problems that use alternative problem representations (e.g. graphical problems).
7. The hypothetical pseudo debate tasks, similar to PbI, which were employed in this study, only presented two fictitious students offering potential arguments to the problem. Research should also consider the effects of more than two arguments

presented on students' argumentative and conceptual performance. The use of multiple alternatives in the pseudo-debate is relevant for at least two reasons. The first reason is that in some domains there are more than one alterative conception that might be relevant to students' responses. For instance, in a Newton's II Law task, research (McCloskey, 1983) has shown that students' alternative conceptions may be influenced by the impetus theory where an object moves until force runs out or by the Aristotelian theory that motion is proportional to force. Thus, an argumentative problem in this domain could involve a pseudo-debate between more than two hypothetical debaters. The second reason is that a pseudo-debate between more than two hypothetical debaters is more similar to a small group conversation between three or more students in a study group. Thus, using such a hypothetical pseudo-debate in an argumentation task may make the task more authentic than merely a pseudo-debate between two hypothetical debaters.

8. Argumentative prompts in this study were adopted from prior studies investigating argumentation in various contexts. Instead of implementing generic prompts that target elicitation of the ideal argument structure, research should consider optimizing such prompts for problems in physics. In the present student, the problems themselves, and the hypothetical pseudo-debates were based on research on students' misconceptions. However, the prompts were generic. Specifically, research should investigate how argumentative prompts can be tailored to the context of specific tasks and leverage existing research on students' misconceptions in the task domain.

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APPENDIX A

HOMEWORK PROBLEMS FOR CONTROL CONDITION

PROBLEM 1 – WORK AND KINETIC ENERGY

Adapted from Lawson and McDermott (1987)

You and your friend are trekking across a nearly frictionless frozen lake to a camp on the other side. Two of you are each pulling a sled loaded with camping equipment and supplies. You both notice, however that you are pulling a much heavier load on your sled than your friend. Your friend, knowing that you are taking physics, asks “Suppose we were both to continuously pull our respective sleds with exactly the same force from the same starting point on this shore of the lake all the way to the opposite shore of the lake, which one of us – the one pulling the heavier or the lighter sled – would do more work? Which will have the greater energy?”

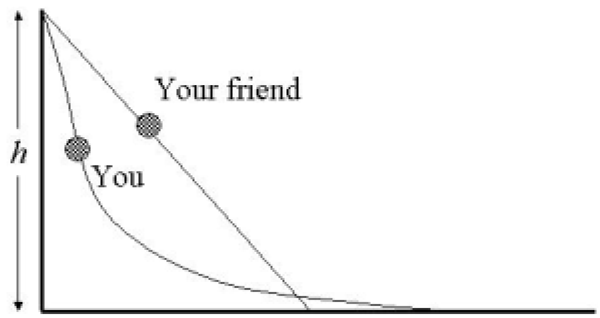
What is your answer? Explain your reasoning.

PROBLEM 2 – ENERGY CONSERVATION

Adapted from Singh and Rosengrant (2003)

You and your friend are skateboarding in a park with nearly frictionless surfaces. You see two ramps – one that goes straight down and the other that curves downward – starting from the same height and ending and the ground level. You and your friend each decide to pick a ramp as shown below and start from rest at the top of each ramp. Your friend, knowing that you are taking physics, asks you "Which one of us will be going faster when we reach the bottom, and who will reach the bottom first?"

What is your answer? Explain your reasoning.



PROBLEM 3 – MOMENTUM CONSERVATION

Adapted from Singh and Rosengrant (2003)

You and your friend are honing your marksmanship skills by shooting bullets into blocks. You decide to fire the bullet into a steel block from which the bullet will bounce off elastically with the same speed at which it hit the block. Your friend decides to use the same gun from the same distance, but fire the bullet into a wooden block of mass equal to the steel block, such that the bullet will get embedded in the wooden block. Knowing that you are taking physics, your friend asks "I wonder which block will take off faster after the collision?"

What is your answer? Explain your reasoning.

PROBLEM 4 – MOMENTUM AND IMPULSE

Adapted from Singh & Rosengrant (2003)

You and your friend are going cycling. At one point, you are going downhill and the brakes fail. You manage to steer the bike away from a concrete wall and into a haystack. As you get up escaping without serious injury, your friend, who knows you are taking physics asks "Why, based on physics, did you not get as hurt now as we would have if you had ridden into the concrete wall?"

What is your answer? Explain your reasoning.

PROBLEM 5 – GRAVITATION, NEWTON'S III LAW

Modified from Hestenes et al. (1992)

You and your friend hear a news item about a satellite that is recently launched into orbit. Your friend asks. "Does the satellite exert a force on the Earth? If so, how does it compare with the force exerted by the Earth on the satellite, and why doesn't the force exerted by the satellite on the Earth mess up the Earth's rotation?"

What is your answer? Explain your reasoning.

APPENDIX B

HOMEWORK PROBLEMS FOR GUIDED CONSTRUCT CONDITION

PROBLEM 1 – WORK AND KINETIC ENERGY

Adapted from Lawson and McDermott (1987)

You and your friend are trekking across a nearly frictionless frozen lake to a camp on the other side. Two of you are each pulling a sled loaded with camping equipment and supplies. You both notice, however that you are pulling a much heavier load on your sled than your friend. Your friend, knowing that you are taking physics, asks "Suppose we were both to continuously pull our respective sleds with exactly the same force from the same starting point on this shore of the lake all the way to the opposite shore of the lake, which one of us – the one pulling the heavier or the lighter sled – would do more work? Which will have the greater energy?"

What is your answer?

- Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.

  In your argument, consider:
  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?

PROBLEM 2 – ENERGY CONSERVATION

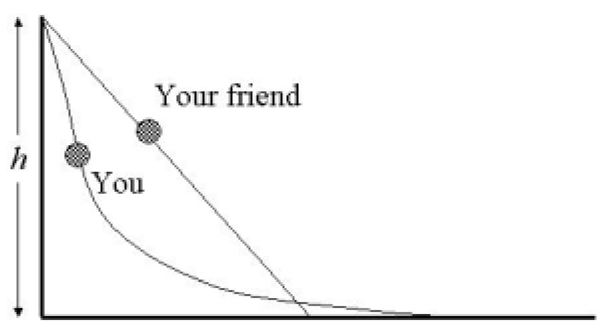
Adapted from Singh and Rosengrant (2003)

You and your friend are skateboarding in a park with nearly frictionless surfaces. You see two ramps – one that goes straight down and the other that curves downward – starting from the same height and ending and the ground level. You and your friend each decide to pick a ramp as shown below and start from rest at the top of each ramp. Your friend, knowing that you are taking physics, asks you "Which one of us will be going faster when we reach the bottom, and who will reach the bottom first?"

What is your answer?

- Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.

  In your argument, consider:
  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?



PROBLEM 3 – MOMENTUM CONSERVATION

Adapted from Singh and Rosengrant (2003)

You and your friend are honing your marksmanship skills by shooting bullets into blocks. You decide to fire the bullet into a steel block from which the bullet will bounce off elastically with the same speed at which it hit the block. Your friend decides to use the same gun from the same distance, but fire the bullet into a wooden block of mass equal to the steel block, such that the bullet will get embedded in the wooden block. Knowing that you are taking physics, your friend asks "I wonder which block will take off faster after the collision?"

What is your answer?

- ➢ Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.

  HINT: In your argument, you may want to consider:
  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?

PROBLEM 4 – MOMENTUM AND IMPULSE

Adapted from Singh and Rosengrant (2003)

You and your friend are going cycling. At one point, you are going downhill and the brakes fail. You manage to steer the bike away from a concrete wall and into a haystack. As you get up escaping without serious injury, your friend, who knows you are taking physics asks "Why, based on physics, did you not get as hurt now as we would have if you had ridden into the concrete wall?"

What is your answer?

- Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.

  HINT: In your argument, you may want to consider:

  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?

PROBLEM 5 – GRAVITATION, NEWTON'S III LAW

Modified from Hestenes et al. (1992)

You and your friend hear a news item about a satellite that is recently launched into orbit. Your friend asks. "Does the satellite exert a force on the Earth? If so, how does it compare with the force exerted by the Earth on the satellite, and why doesn't the force exerted by the satellite on the Earth mess up the Earth's rotation?"

What is your answer?

- ➢ Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.

  HINT: In your argument, you may want to consider:
  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?

APPENDIX C

HOMEWORK PROBLEMS FOR GUIDED EVALUATE CONDITION

PROBLEM 1 – WORK AND KINETIC ENERGY

Adapted from Lawson and McDermott (1987)

You and your friends are trekking across a nearly frictionless frozen lake to a camp on the other side. Two of you are each pulling a sled loaded with camping equipment and supplies. You both notice, however that one of you is pulling a much heavier load on their sled than the other one. Your friend, knowing that you are taking physics, asks "Suppose we were both to continuously pull our respective sleds with exactly the same force from the same starting point on this shore of the lake all the way to the opposite shore of the lake, which one of us – the one pulling the heavier or the lighter sled – would do more work? Which will have the greater energy?" Two other friends who are trekking with you, and who are also taking physics, jump in to answer.

Bill: "You will clearly need to do the greater amount of work on the heavier sled, since it is heavier and because of that, the heavier cart sled will also have greater energy because whatever work you do is converted into kinetic energy."

Bob: "Of course, the heavier sled will need more work, but the heavier sled will be have a smaller kinetic energy, because kinetic energy depends upon the mass and the square of the speed and although the heavier sled has a greater mass, it has a smaller speed, so it will have a smaller kinetic energy."

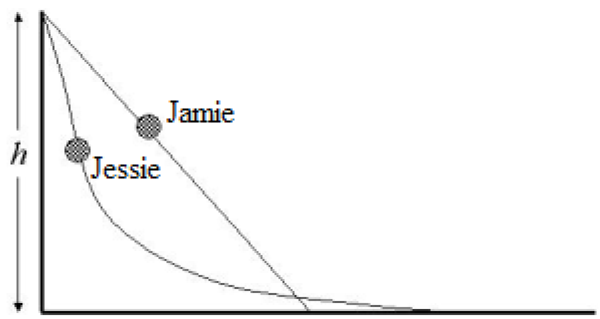
Which one of them, Bill or Bob, do you agree with? Or do you have a different argument?

- Explain, elaborate, and justify your preferred solution.
  In your solution, consider:
  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
  - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

PROBLEM 2 – ENERGY CONSERVATION

Adapted from Singh and Rosengrant (2003)

You and your friends are skateboarding in a park with nearly frictionless surfaces. You see two ramps – one that goes straight down and the other that curves downward – starting from the same height and ending and the ground level. Two of your friends, each decide to pick a ramp as shown below and start from rest at the top of each ramp. A third friend, knowing that you are all taking physics, asks "Which one of us will be going faster when we reach the bottom, and who will reach the bottom first?" Jamie and Jessie both jump in to answer the question.



Jamie: "I will of course reach first because I have a shorter track. I will also reach faster because my track is a more downwardly directed than Jessie's track most of my energy will be converted into downward speed and I would be faster when I reach down"

Jessie: "No, you're wrong! I will reach first because, my track is steeper initially, so I gain speed initially and keep that advantage until the end. For the same reason, I will also have a greater speed at the end of the track."

Which one of them, Jamie or Jessie, do you agree with? Or do you have a different argument?

- Explain, elaborate, and justify your preferred solution.
  In your solution, consider:
    - What evidence and reasons supports your selection?
    - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
    - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

PROBLEM 3 – MOMENTUM CONSERVATION

Adapted from Singh and Rosengrant (2003)

You and your friends are honing your marksmanship skills by shooting bullets into blocks. You decide to fire the bullet into a steel block from which the bullet will bounce off elastically with the same speed at which it hit the block. Your friend decides to use the same gun from the same distance, but fire the bullet into a wooden block of mass equal to the steel block, such that the bullet will get embedded in the wooden block. Knowing that you are taking physics, your friend asks "I wonder which block will take off faster after the collision?" Two other friends who are with you, and who are also taking physics, answer.

Bill: "The wood block, because it has gained the motion of the bullet, while the other bullet does not impart its motion to the steel block."

Bob: "No, it is the steel block, because the bullet bounces off from the steel block and gives it all the motion."

Which one of them, Bill or Bob, do you agree with? Or do you have a different argument?

➢ Explain, elaborate, and justify your preferred solution.
  HINT: In your solution, you may want to consider:
  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
  - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

PROBLEM 4 – MOMENTUM AND IMPULSE

Adapted from Singh and Rosengrant (2003)

You and your friends are going cycling. At one point, you are going downhill and the brakes fail. You manage to steer the bike away from a concrete wall and into a haystack. As you get up escaping without serious injury, your friend, who knows you are taking physics asks "Why, based on physics, did you not get as hurt now as we would have if you had ridden into the concrete wall?" Two other friends, who are also taking physics, answer the question.

Jamie: "The haystack gives you a smaller impulse than the concrete wall."

Jessie: "No, it is not the impulse that is smaller, rather your change in momentum is smaller if you hit the haystack than if you hit the concrete wall."

Which one of them, Jamie or Jessie, do you agree with? Or do you have a different argument?

- Explain, elaborate, and justify your preferred solution.
  HINT: In your solution, you may want to consider:
  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
  - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

PROBLEM 5 – GRAVITATION, NEWTON'S III LAW

Modified from Hestenes et al. (1992)

You and your friend hear a news item about a satellite that is recently launched into orbit. Your friend asks. "Does the satellite exert a force on the Earth? If so, how does it compare with the force exerted by the Earth on the satellite, and why doesn't the force exerted by the satellite on the Earth mess up the Earth's rotation?" Two other friends jump in to answer.

Jamie: "No. The satellite does not exert any force on the Earth. We know this because, if it did, each time a satellite is launched it would mess up the Earth's rotation and timing of day and night would get affected, which we know does not happen."

Jessie: "Actually, the satellite does exert a force on the Earth, but because the satellite is very small compared to the Earth, the satellite exerts a force on the Earth that is much smaller than the one the earth does on it, so it fails to cause any noticeable change in the Earth's rotation or affect the timing of the day and night."

Which one of them, Jessie or Jamie, do you agree with? Or do you have a different argument?

- Explain, elaborate, and justify your preferred solution.
  HINT: In your solution, you may want to consider:
  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
  - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

APPENDIX D

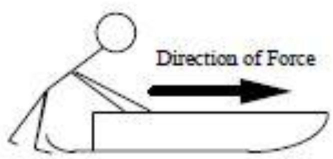
FORCE MOTION CONCEPT EVALUATION (Thornton & Sokokoff, 1998)

FORCE AND MOTION CONCEPTUAL EVALUATION

__Directions:__ Answer questions 1-47 in spaces on the answer sheet. Be sure your name is on the answer sheet. __Answer question 46a also on the answer sheet.__ Hand in the questions and the answer sheet.

A sled on ice moves in the ways described in questions 1-7 below. *Friction is so small that it can be ignored.* A person wearing spiked shoes standing on the ice can apply a force to the sled and push it along the ice. Choose the __one__ force (A through G) which would **keep the sled moving** as described in each statement below.

You may use a choice more than once or not at all but choose only one answer for each blank. If you think that none is correct, answer choice **J**.

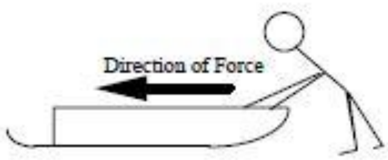


A. The force is toward the **right** and is **increasing** in strength (magnitude).

B. The force is toward the **right** and is of **constant** strength (magnitude).

C. The force is toward the **right** and is **decreasing** in strength (magnitude).

D. No applied force is needed



E. The force is toward the **left** and is **decreasing** in strength (magnitude).

F. The force is toward the **left** and is of **constant** strength (magnitude).

G. The force is toward the **left** and is **increasing** in strength (magnitude).

___1. Which force would keep the sled moving toward the right and speeding up at a steady rate (constant acceleration)?

___2. Which force would keep the sled moving toward the right at a steady (constant) velocity?

___3. The sled is moving toward the right. Which force would slow it down at a steady rate (constant acceleration)?

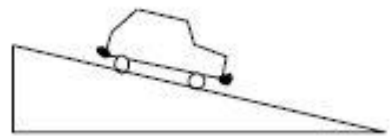
___4. Which force would keep the sled moving toward the left and speeding up at a steady rate (constant acceleration)?

___5. The sled was started from rest and pushed until it reached a steady (constant) velocity toward the right. Which force would keep the sled moving at this velocity?

___6. The sled is slowing down at a steady rate and has an acceleration to the right. Which force would account for this motion?

___7. The sled is moving toward the left. Which force would slow it down at a steady rate (constant acceleration)?

Questions 8-10 refer to a toy car which is given a quick push so that it rolls up an inclined ramp. After it is released, it rolls up, reaches its highest point and rolls back down again. *Friction is so small it can be ignored.*



Use one of the following choices (**A** through G) to indicate the **net force** acting on the car for each of the cases described below. Answer choice **J** if you think that none is correct.

(A) Net **constant** force **down** ramp
(B) Net **increasing** force **down** ramp
(C) Net **decreasing** force **down** ramp
(D) Net force zero
(E) Net **constant** force **up** ramp
(F) Net **increasing** force **up** ramp
(G) Net **decreasing** force **up** ramp

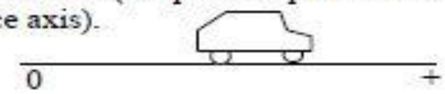
______8. The car is moving up the ramp after it is released.
______9. The car is at its highest point.
______10. The car is moving down the ramp.

Questions 11-13 refer to a coin which is tossed straight up into the air. After it is released it moves upward, reaches its highest point and falls back down again. Use one of the following choices (**A** through G) to indicate the force acting on the coin for each of the cases described below. Answer choice **J** if you think that none is correct. **Ignore any effects of air resistance.**

A. The force is **down** and constant.
B. The force is **down** and increasing
C. The force is **down** and decreasing
D. The force is zero.
E. The force is **up** and constant.
F. The force is **up** and increasing
G. The force is **up** and decreasing

______11. The coin is moving upward after it is released.
______12. The coin is at its highest point.
______13. The coin is moving downward.

Questions 14-21 refer to a toy car which can move to the right or left along a horizontal line (the positive part of the distance axis).



Assume that friction is so small that it can be ignored.

A force is applied to the car. Choose the one force graph (**A** through **H**) for each statement below which could allow the described motion of the car to continue.

You may use a choice more than once or not at all. If you think that none is correct, answer choice **J**.

__14. The car moves toward the right (away from the origin) with a steady (constant) velocity.

__15. The car is at rest.

__16. The car moves toward the right and is speeding up at a steady rate (constant acceleration).

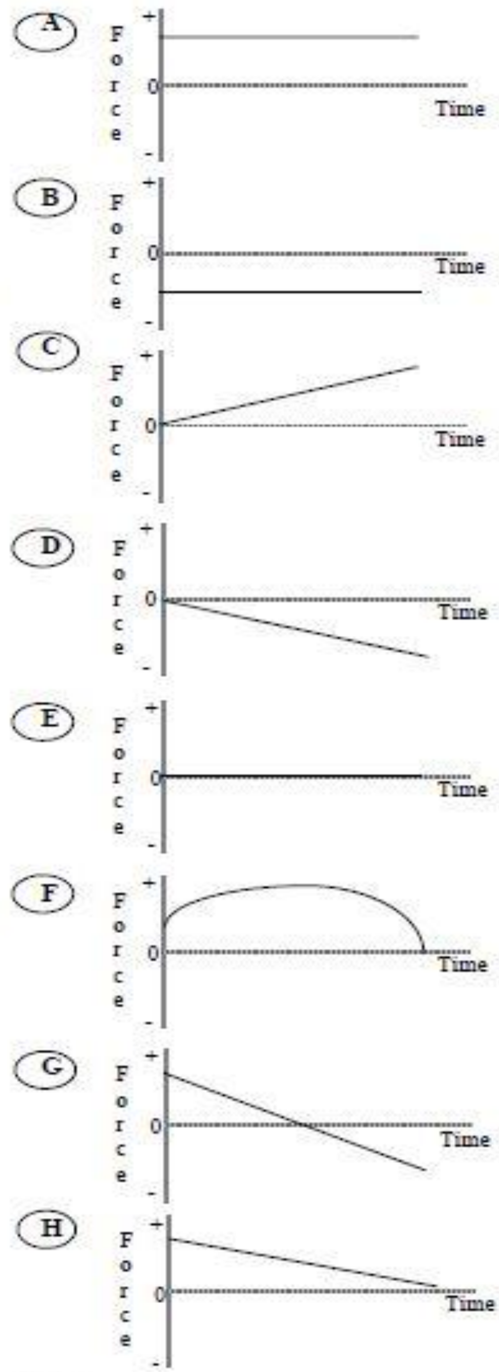
__17. The car moves toward the left (toward the origin) with a steady (constant) velocity.

__18. The car moves toward the right and is slowing down at a steady rate (constant acceleration).

__19. The car moves toward the left and is speeding up at a steady rate (constant acceleration).

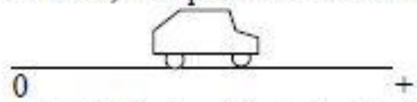
__20. The car moves toward the right, speeds up and then slows down.

__21. The car was pushed toward the right and then released. Which graph describes the force after the car is released.



(J) None of these graphs is correct.

Questions 22-26 refer to a toy car which can move to the right or left on a horizontal surface along a straight line (the + distance axis). The positive direction is to the right.



Different motions of the car are described below. Choose the letter (A to G) of the **acceleration-time** graph which corresponds to the motion of the car described in each statement.

You may use a choice more than once or not at all. If you think that none is correct, answer choice J.

(J) None of these graphs is correct.

_____22. The car moves toward the right (away from the origin), speeding up at a steady rate.

_____23. The car moves toward the right, slowing down at a steady rate.

_____24. The car moves toward the left (toward the origin) at a constant velocity.

_____25. The car moves toward the left, speeding up at a steady rate.

_____26. The car moves toward the right at a constant velocity.

Questions 27-29 refer to a coin that is tossed straight up into the air. After it is released it moves upward, reaches its highest point and falls back down again. Use one of the following choices (A through G) to indicate the acceleration of the coin during each of the stages of the coin's motion described below. Take **up** to be the **positive** direction. Answer choice **J** if you think that none is correct.

- **A.** The acceleration is in the negative direction and constant.
- **B.** The acceleration is in the negative direction and increasing
- **C.** The acceleration is in the negative direction and decreasing
- **D.** The acceleration is zero.
- **E.** The acceleration is in the positive direction and constant.
- **F.** The acceleration is in the positive direction and increasing
- **G.** The acceleration is in the positive direction and decreasing

___27. The coin is moving upward after it is released.

___28. The coin is at its highest point.

___29. The coin is moving downward.

Questions 30-34 refer to collisions between a car and trucks. For each description of a collision (30-34) below, choose the one answer from the possibilities **A** though **J** that best describes the forces between the car and the truck.

- A. The truck exerts a greater amount of force on the car than the car exerts on the truck.
- B. The car exerts a greater amount of force on the truck than the truck exerts on the car.
- C. Neither exerts a force on the other; the car gets smashed simply because it is in the way of the truck.
- **D.** The truck exerts a force on the car but the car doesn't exert a force on the truck.
- **E.** The truck exerts the same amount of force on the car as the car exerts on the truck.
- **F.** Not enough information is given to pick one of the answers above.
- **J.** None of the answers above describes the situation correctly.

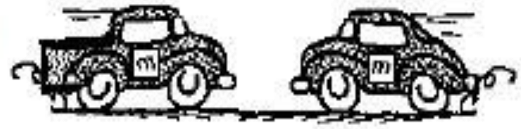
In questions 30 through 32 the truck is much heavier than the car .

_____30. They are both moving at the same speed when they collide. Which choice describes the forces?

_____31. The car is moving much faster than the heavier truck when they collide. Which choice describes the forces?

_____32. The heavier truck is standing still when the car hits it. Which choice describes the forces?

In questions 33 and 34 the truck is a small pickup and is the same weight as the car.



_____33. Both the truck and the car are moving at the same speed when they collide. Which choice describes the forces?

_____34. The truck is standing still when the car hits it. Which choice describes the forces?

Questions 35-38 refer to a large truck which breaks down out on the road and receives a push back to town by a small compact car.

Pick one of the choices A through J below which correctly describes the forces between the car and the truck for each of the descriptions (35-38).

A. The force of the car pushing against the truck is equal to that of the truck pushing back against the car.

B. The force of the car pushing against the truck is less than that of the truck pushing back against the car.

C. The force of the car pushing against the truck is greater than that of the truck pushing back against the car.

D. The car's engine is running so it applies a force as it pushes against the truck, but the truck's engine isn't running so it can't push back with a force against the car.

E. Neither the car nor the truck exert any force on each other. The truck is pushed forward simply because it is in the way of the car.

J. None of these descriptions is correct.

_____35. The car is pushing on the truck, but not hard enough to make the truck move.

_____36. The car, still pushing the truck, is **speeding up** to get to cruising speed.

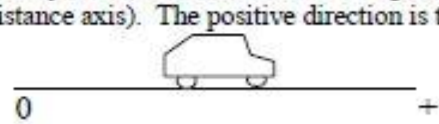
_____37. The car, still pushing the truck, is at cruising speed and continues to travel at the **same speed**.

_____38. The car, still pushing the truck, is at cruising speed when the truck puts on its brakes and causes the car to **slow down**.

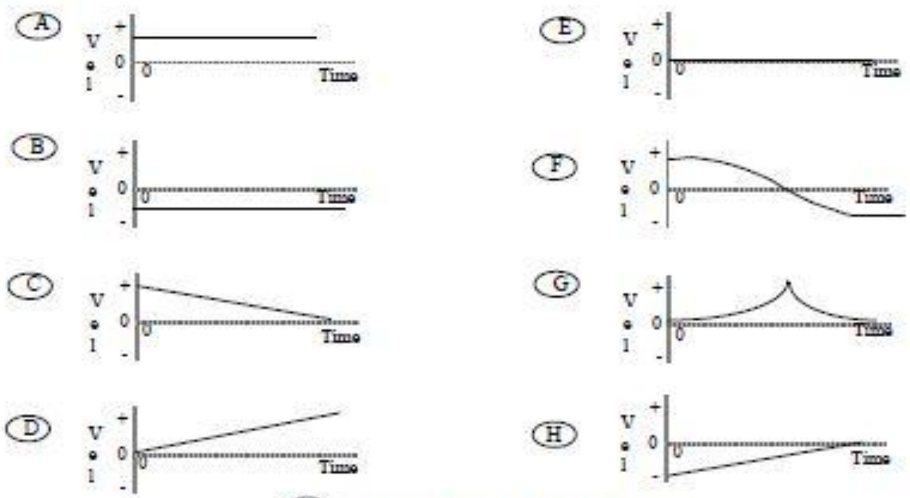
____39. Two students sit in identical office chairs facing each other. Bob has a mass of 95 kg, while Jim has a mass of 77 kg. Bob places his bare feet on Jim's knees, as shown to the right. Bob then suddenly pushes outward with his feet, causing both chairs to move. In this situation, while Bob's feet are in contact with Jim's knees,

A. Neither student exerts a force on the other.
B. Bob exerts a force on Jim, but Jim doesn't exert any force on Bob.
C. Each student exerts a force on the other, but Jim exerts the larger force.
D. Each student exerts a force on the other, but Bob exerts the larger force.
E. Each student exerts the same amount of force on the other.
J. None of these answers is correct.

Questions 40-43 refer to a toy car which can move to the right or left along a horizontal line (the positive portion of the distance axis). The positive direction is to the right.



Choose the correct velocity-time graph (**A** - **G**) for each of the following questions. You may use a graph more than once or not at all. If you think that none is correct, answer choice **J**.



(J) None of these graphs is correct.

___40. Which velocity graph shows the car moving toward the right (away from the origin) at a steady (constant) velocity?
___41. Which velocity graph shows the car reversing direction?
___42. Which velocity graph shows the car moving toward the left (toward the origin) at a steady (constant) velocity?
___43. Which velocity graph shows the car increasing its *speed* at a steady (constant) rate?

A sled is pulled up to the top of a hill. The sketch above indicates the shape of the hill. At the top of the hill the sled is released from rest and allowed to coast down the hill. At the bottom of the hill the sled has a speed v and a kinetic energy E (the energy due to the sled's motion). Answer the following questions. ***In every case friction and air resistance are so small they can be ignored.***

__44. The sled is pulled up a **steeper** hill of the **same** height as the hill described above. How will the velocity of the sled at the bottom of the hill (after it has slid down) compare to that of the sled at the bottom of the original hill? Choose the best answer below.

- **A**. The speed at the bottom is greater for the steeper hill.
- **B**. The speed at the bottom is the same for both hills.
- **C**. The speed at the bottom is greater for the original hill because the sled travels further.
- **D**. There is not enough information given to say which speed at the bottom is faster.
- **J**. None of these descriptions is correct.

__45. Compare the kinetic energy (energy of motion) of the sled at the bottom for the original hill and the steeper hill in the previous problem. Choose the best answer below.

- **A**. The kinetic energy of the sled at the bottom is greater for the steeper hill.
- **B**. The kinetic energy of the sled at the bottom is the same for both hills.
- **C**. The kinetic energy at the bottom is greater for the original hill.
- **D**. There is not enough information given to say which kinetic energy is greater.
- **J**. None of these descriptions is correct.

__46. The sled is pulled up a **higher** hill that is **less steep** than the original hill described before question 44. How does the speed of the sled at the bottom of the hill (after it has slid down) compare to that of the sled at the bottom of the original hill?

- **A**. The speed at the bottom is greater for the higher but less steep hill than for the original.
- **B**. The speed at the bottom is the same for both hills.
- **C**. The speed at the bottom is greater for the original hill.
- **D**. There is not enough information given to say which speed at the bottom is faster.
- **J**. None of these descriptions is correct.

46a. Describe in words your reasoning in reaching your answer to question 46. (**Answer on the answer sheet** and use as much space as you need)

_47. For the higher hill that is less steep, how does the kinetic energy of the sled at the bottom of the hill after it has slid down compare to that of the original hill?

- **A**. The kinetic energy of the sled at the bottom is greater for the higher but less steep hill.
- **B**. The kinetic energy of the sled at the bottom is the same for both hills.
- **C**. The kinetic energy at the bottom is greater for the original hill.
- **D**. There is not enough information given to say which kinetic energy is greater.
- **J**. None of these descriptions is correct.

APPENDIX E

INFORMATION REVIEW BOARD APPROVAL

Campus Institutional Review Board
University of Missouri-Columbia

485 McReynolds Hall
Columbia, MO 65211-1150
PHONE: (573) 882-9585
FAX: (573) 884-0663

January 3, 2012

Principal Investigator: Rebello, Carina Marie
Department: Physics

Your Application to project entitled *Relationships between Undergraduates' Argumentation Skills, Conceptual Quality, and Problem Solving Strategies in Introductory Physics* was reviewed and approved by the MU Campus Institutional Review Board according to terms and conditions described below:

IRB Project Number	1200448
Initial Application Approval Date	January 3, 2012
IRB Expiration Date	January 3, 2013
Level of Review	Exempt
Regulation	45 CFR 46.101.b.1 and 45 CFR 46.101.b.2
Project Status	Active - Open to Enrollment
Risk Level	Minimal Risk

The principal investigator (PI) is responsible for all aspects and conduct of this study. The PI must comply with the following conditions of the approval:

1. No subjects may be involved in any study procedure prior to the IRB approval date or after the expiration date.
2. All unanticipated problems, serious adverse events, and deviations must be reported to the IRB within 5 days.
3. All modifications must be IRB approved by submitting the Exempt Amendment prior to implementation unless they are intended to reduce risk.
4. All recruitment materials and methods must be approved by the IRB prior to being used.
5. The Annual Exempt Certification Form must be submitted to the IRB for review and approval at least 30 days prior to the project expiration date.
6. Maintain all research records for a period of seven years from the project completion date.
7. Utilize the IRB stamped document informing subjects of the research and other approved research documents located within the document storage section of eIRB.

If you have any questions, please contact the Campus IRB at 573-882-9585 or umcresearchcirb@missouri.edu.

Thank you,

Charles Borduin, PhD
Campus IRB Chair

APPENDIX F

STUDENT INFORMED CONSENT DOCUMENT

Campus Institutional Review Board

University of Missouri

STUDENT INFORMED CONSENT DOCUMENT

Project Title: Relationships between Undergraduate' Argumentation Skills, Conceptual Quality, and Problem Solving Strategies in Introductory Physics

You are invited to participate in a research study related to the course University Physics 1 (2750), conducted by Carina Rebello. The purpose of this study is to investigate how you solve physics problems in your course homework and exams and your physics conceptual understanding and quality of problem solutions. The study will involve regular class activities and the potential to participate in three interview sessions. This research is being conducted to help understand how students solve physics problems supporting argumentation and the scientific quality of problem solutions. When you are invited to participate in research, you have the right to be informed about the study procedures so that you can decide whether you want to consent to participation. This form may contain words that you do not know. Please ask the researcher to explain any words or information that you do not understand.

Researcher's Name(s): Carina M. Rebello (Graduate Student), Dr. Lloyd Barrow (Professor and Advisor)

Researcher's Contact Information: Email: cp5xc@mail.mizzou.edu

Your Rights You have the right to know what you will be asked to do so that you can decide whether or not to be in the study. Your participation is **voluntary** and **confidential**. You do not have to be in the study if you do not want to. You may refuse to be in the study and nothing will happen. If you do not want to continue to be in the study, you may stop at any time without penalty or loss of benefits to which you are otherwise entitled.

Purpose of Study The purpose of this research is to how introductory calculus-based students solve physics problems supporting argumentation that are embedded in the course homework and exams. Also to explore the scientific conceptual quality of physics problem solutions and what kinds of arguments are constructed within the solutions. Results from your responses to the homework and exam problems will be compared with your exam grades, responses to the Force Motion Concept Evaluation, and responses to the Views about Science Survey in order to address the purposes of this study.

Length of Your Involvement in Study Your involvement in the study will be limited to the completion of regular class activities. Additionally you may have the opportunity to volunteer and participate in three 60 minute interviews (Phase II of the study).

What you are being asked to do In this study you will be asked to volunteer and provide consent to analyze your responses to home work and course exam problems. Additionally you will be asked to provide consent for Carina Rebello to access your course exam grades, but NOT your course grades, from the course professor. Grades for each exam will only be received after the completion of the course when grades are submitted. In Phase II (if you volunteer) you may be invited to participate in three (3) interview sessions lasting approximately 60 minutes each during the first half of the semester. During the interviews you will be asked to share your how any why you solved your previously completed homework and exam problems as you did. Additionally you will be asked to solve approximately two physics problems and share what strategies you are taking to solve them. The interviews will be audio recorded and video recorded for analysis purposes.

Total Number of Participants in Study There will be around 300 students who will participate in this study. Approximately 24 students will participate in Phase II (interview sessions).

Risks of Being in Study Risks are minimal. Your participation in this study is not expected to cause you any risks greater than those encountered in everyday life. The course professor will not know if you choose or do not choose to participate in this study. Your participation or lack of will not influence your course grade.

Benefits of Being in Study Your participation in this study will benefit the science education community as a whole. With your help, the research can inform instructional practices in introductory physics to better help enhance students understanding of physics concepts and problem solving skills.

Other Options You also have the option of not participating in this study, and will not be penalized for your decision. By choosing to not participate in this study you will still need to complete normal class activities but you will not have your homework and exam responses analyzed and exam grades accessed for the purposes of this study.

Confidentiality Your identity and participation will remain confidential. Your name or information will NOT be provided to anyone outside of the research. Data collected from you will only be shared between the two researchers who are listed on this form. Pseudonyms will be generated upon identification of participants and will be used in all stages of the project. When the data is presented in a public sphere, such as a journal or talk, you will not be identified by name or any other identifiable feature. The data will be securely stored for no more than seven years in a locked safe before it is destroyed. All data generated will be used for the purpose of analysis for this project and may be used again in the future to help answer alternative questions based on this project.

Privacy The information you will provide us is considered will be kept confidential. Please see above.

Your Compensation If you are selected to participate in Phase II (interview sessions) of this study, you will be compensated $30 if you complete all three 60 minute interviews. The compensation for participation in each interview will be prorated as follows: If you decide to leave the interview sessions early, you will be compensated as follows: $0 for the first 15 minutes, $5 for 15-30 minutes, $8 for 30-45 minutes, $10 for longer than 45 minutes. If you decide to participate in only the first interview you will be compensated $10. If you participate two out of the three interviews completely, you will be compensated $20.

Will the researcher tell me if something changes in the study? If you do not understand what is written above, please contact the investigator listed below. You will be informed of any new information discovered during the course of this study that might influence your health, welfare, or willingness to be in this study.

Where can I learn more about participating in research? The Campus Institutional Review Board offers educational opportunities to research participants, prospective participants, or their communities to enhance their understanding of research involving human participants, the IRB process, the responsibilities of the investigator and the IRB. You may access the Campus IRB website to learn more about the human subject research process at http://www.research.missouri.edu/cirb/index.htm

Who do I contact if I have questions, concerns, or complaints? You may ask questions, voice concerns or complaints to the research team below.

This project has been reviewed and approved by the University of Missouri – Columbia Human Subject Review Board. The Board believes the research procedures adequately safeguard your privacy, welfare, civil liberties, and rights. For additional information regarding human subject participation in this research, please contact the University of Missouri – Columbia IRB officer at (573) 882-9585.

If you have any questions regarding your rights as a participant in this research and/or concerns about the study, or if you feel under any pressure to enroll or to continue to participate in this study, you may contact the University of Missouri Campus Institutional

Review Board (which is a group of people who review the research studies to protect participants' rights) at (573) 882-9585 or umcresearchcirb@missouri.edu.

<u>Investigator Contact Information</u>

Carina M. Rebello *Address:* University of Missouri Learning, Teaching, and Curriculum Science Education Center 321 Townsend Hall Columbia, MO 65211, USA *Phone number*: 785-585-7171 *E-mail address:* cp5xc@mail.mizzou.edu	**Dr. Lloyd Barrow** *Address:* University of Missouri Learning, Teaching, and Curriculum Science Education Center 321 Townsend Hall Columbia, MO 65211, USA *Phone number*: 573-882-7457 *E-mail address:* BarrowL@missouri.edu

<u>Who do I contact if I have questions about my rights, concerns, complaints or comments about the research?</u> You may contact the Campus Institutional Review Board if you have questions about your rights, concerns, complaints or comments as a research participant. If you have any questions regarding your rights as a participant in this research and/or concerns about the study, or if you feel under any pressure to enroll or to continue to participate in this study, you may contact the University of Missouri Campus Institutional Review Board (which is a group of people who review the research studies to protect participants' rights) at (573) 882-9585 or umcresearchcirb@missouri.edu.

<u>Will I get a copy of this form to take with me?</u> A copy of this Informed Consent form will be given to you before you participate in the research.

SIGNATURES I have read this consent form and my questions have been answered. My signature means that:

I consent to allow the researchers of this study to use the data from my responses to homework and exam problems, responses to Force Motion Concept Evaluation and Views about Science Survey and my interviews. I also consent to allow the researchers to request the professor of my physics course at MU this semester to provide them my scores on each exam in the class, but NOT the overall course grade. I can remove myself from the study at any time.

☐ Check box indicating the you are 18 years or older

____
Print Name

____________________ _______
Your Signature Date

____________________ _______
Investigator's Signature Date

(If you are selected to participate in Phase II (interview sessions) of this study, you will be compensated $30 if you complete all three 60 minute interviews)

Are you willing to volunteer and participate in three interview sessions (Phase II) of this study? YES or NO

If so, please provide your preferred email address to be contacted by:________________________________

If you are willing to participate, please mark which day(s) and time(s) are generally available for you to meet for approximately 60 minutes.

	Monday	Tuesday	Wednesday	Thursday	Friday
8:00-9:00am					
9:00-10:00am					
10:00-11:00am					
11:00am-12:00pm					
12:00-1:00pm					
1:00-2:00pm					
2:00-3:00pm					
4:00-5:00pm					
5:00-6:00pm					
6:00-7:00pm					
7:00-8:00pm					

APPENDIX G

CONCEPTUAL QULITY RUBRIC WITH EXCERPTS

CONCEPTUAL QUALITY RUBRIC

Points	Description	Excerpt – Homework, Problem 1	Notes
0	Incorrect, little or no correct scientific reasoning	"Well since my sled weighs more, it will require me to exert more work on it just to get it going from start and up to a sufficient speed. However, once my sled gets going, it will have greater energy than the lighter one since it weighs considerably more and it has more and greater forces acting on it. Since it has greater forces acting on it due to its size, it will gain more momentum than the smaller/lighter sled."	Incorrectly states and reasons that a heavier sled does more work. Also incorrectly states and reasons that the heavier sled will have more energy. In fact, work and energy should be equal for both a heavier and lighter sled. Does not apply meaning of work and relation of work to kinetic energy.
1	Incorrect answer, some correct scientific reasoning	"Work is force times distance and it would take more force to move the heavier sled therefore the sled that I am carrying would require more work. Energy is work over time so I would be doing more work over the same distance meaning I have the greater energy."	Correctly states the meaning of work but inappropriately applies it with the given problem information which leads to an incorrect solution. Also incorrectly reasons with a work – energy relation which leads to an incorrect solution about energy.
2	Correct answer, little or some incorrect scientific reasoning	"Since there is no slope and no friction the additional weight adds no work needed to pull the sled. We would have to do the same amount of work and it will have the same amount of energy."	Correctly states that work and energy will be the same. Does not apply any scientific reasoning to describe why work and energy are the same.
3	Correct answer, with correct scientific reasoning	"Work is equal to force times displacement. Both my friend and I are exerting the same force and traveling the same distance; therefore, we are doing the same amount of work. Work is the change in kinetic energy and in this situation there is no potential energy involved so we both have the same energy."	Correctly states that work and energy would be the same. Correctly applies the definition of work and the relation of work to kinetic energy as rational.

APPENDIX H

ARGUMENATION QUALITY RUBRIC WITH EXCERPTS

ARGUMENTATION QUALITY RUBRIC

Adapted from Sadler and Fowler (2006)

Points	Description	Excerpt – Homework, Problem 1	Notes
0	No justification provided to position given	"We both produce the same amount of work. Both sleds have the same amount of energy at the other end of the lake."	Only claim is given, did not support why both work and energy would be the same.
1	Justification with evidence but no grounds	"Since both of them are pulling with the same force they will do the same work. If both of them have the same work then that means they have the same energy."	Claim is justified with only reference to "same force" given in problem information.
2	Justification with single/multiple evidence + simple grounds	"They would each do the same amount of work because work=force*distance. Each person has the same numerical values for force and distance so their work will be the same. The person pulling the sled with the heavier weight will have greater energy. Since the energy equation takes into account the mass of an object, the person pulling the heavier weight will have a higher numerical value for energy."	Claim is justified with reference to work equation. Connects work equation to problem information about force and distance. Same amount of justification is applied to energy claim.

Points	Description	Excerpt – Homework, Problem 1	Notes
3	Justification with single/multiple evidence + elaborated (i.e. multiple) grounds	"They would do the same amount of work since work is independent of mass if the forces are equal. Work is equal to the force applied on an object multiplied by the distance the object travels. Since we are both applying equal forces on the object over the same distance the work done by each of us is the same. Although they both did the same amount of work, the person pulling the lighter sled will apply more energy. The energy used to pull the sleds was all kinetic energy and none of it was lost due to friction so all the energy used is kinetic energy. This is equal to 1/2 times the mass times the velocity squared. If they both pull with the same force, the heavier sled will be moving slower than the lighter one since Force equals the mass times the acceleration. So looking at the energy, the lighter sled will have more energy since although it has less mass, it has a higher acceleration and thus higher velocity so the energy would be greater."	Justifies claim about work with reference to problem information about force and distance, identifies work equation, also identifies that work is independent of mass, and relates problem information to equation. Justifies claim about energy with reference to amount of friction with leads only to kinetic energy, identifies equation for kinetic energy, identifies and applies problem information to equation, and also connects problem information to another equation.
4	Justification with single/multiple evidence + elaborated grounds and counterclaim(s)	"My argument is that both sleds will do the same amount of work because of a frictionless surface, and the lighter sled will have greater energy. The reason for the same amount of work on both is that mass does not play a factor in the work equation. Mass does however play a factor in Kinetic energy, and that is why the lighter sled will have a larger kinetic energy, and a higher velocity. A classmate may think the heavier sled will require more work, because they think the heavier sled due to friction would require more physical work."	Claim is further justified with reference to a counterargument that a classmate may have.

Points	Description	Excerpt – Homework, Problem 1	Notes
5	Justification with single/multiple evidence + elaborated grounds, counterclaim(s), and rebuttal(s)	"Both my friend and I would be doing the same amount of work. The evidence supporting my reason is the fact that work = force * distance. Since we were using the same amount of force, and travelling the same distance across the lake, the work we did would be the same. Also, neither sled would have more energy than the other because the work done by each is the same. An argument made against me would be that the heavier one would be the one that would be more work. They would bring up that since it has more mass, then it would take more force to pull the sled, which would then make the work higher. To this, I would state that the frozen lake is near frictionless, making the weight of the sled irrelevant because friction is the only force that would obstruct your own applied force towards moving the sled, effectively removing mass from the equation, meaning that the work is still the same. The other would be that the smaller sled would have a higher energy because it would be moving faster, but since the work is the same, that means the kinetic energy has to be the same, making the ratio between velocity and mass would be equal for each sled making their energies the same."	Claim is justified with reference to equation or work and relation of work to energy. Also justifies claim what another classmate might say and considerations of how to rebuttal to further defend position.

Note. Grounds refer to warrants, backings, or qualifiers

APPENDIX I

SEMI-STRUCTURED INTERVIEW PROTOCOL

SEMI-STRUCTURED INTERVIEW PROTOCOL

Hello, my name is Carina Rebello. Thank you for participating in this study. Your participation is voluntary. What you will discuss in the interview will not affect your grade in any way and will not be disclosed to anyone else. I am only interested in the process of how and why you solve problems as you do. So, do not worry about whether you get the questions right or wrong. If you are interested in finding out, we can discuss the answers when the interview is done. I want to understand what you are thinking and doing when you solve these problems. For that reason, I would like you to talk your way through it. Please tell me whatever it is you are thinking, what you are doing, and how you are working out each task. Are you comfortable with me video and audio recording?

State date, time, introduce ourselves…

Warm-up Questions – First Interview:

- How is your physics course going for you?
- Have you taken any other physics course prior to this class? [For first interview only]
- What do you expect to take away from your physics course? [For first interview only]
- Can you describe what you typically do when you solve problems related to the topic of __________? How do you go about solving such problems? Please explain why.
- What materials or resources do you typically use when solving physics homework problems?

Interview Questions: Give one or two argumentative problems for students to solve. “Please solve the problem on this sheet and as you do, please walk me through each step, explain your reasoning about it.”

Allow time to solve and observe. As they solve, ask how they solved the problem, what steps did they take, why they did those steps, and what they considered.

- Can you describe how you solved the problem?
- What is the reason you solved the problem the way you did?
- Are there other reasons for why your claim/solution is true?
- You used principle X to solve the problem, are there other strategies to solving the problem?
- Could you have solved the problem differently?
- Can you think of an argument for an alternative solution?
- What did you consider as you solved the problem? Explain why.
- What unstated assumptions did you make while solving the problem?
    - What if your classmates made different assumptions?

- Did you look specifically at the bulleted list while solving the problem?
    - Can you tell me more about how you used the questions in this bulleted list?
- What does argumentation mean to you? Can there be argumentation in physics?
- Can you describe what you mean by evidence?
    - What evidence did you use in the problem?
    - What kinds of evidence might your classmate refer to?
    - What evidence is one more likely to ignore in the problem?
- If someone disagreed with your solution, how could you convince them that your answer is true?
- How is the manner in which you solved the problem similar to or different from other problems you have solved for this topic?

STIMUATED RECALL QUESTIONS

"Here are the problems that you previously completed form your homework. Could you please describe for me how you went about solve these problems."

- Tell me about your solution. Can you describe for me how you solved the problem?
- What is the reason you solved the problem the way you did?
- What did you consider as you solved the problem? Explain why.
- Are there features of the problem that helped you develop your solution? How did it help you?
- How could you have solved this problem in a different way?
- What unstated assumptions did you make while solving the problem?
    - What if your classmates made different assumptions?
- Did you look specifically at the bulleted list while solving the problem?
- Can you describe what you mean by evidence?
    - What evidence did you use in the problem?
    - What kinds of evidence might your classmate refer to?
    - What evidence is one more likely to ignore in the problem?

Thank you for your participation.

APPENDIX J

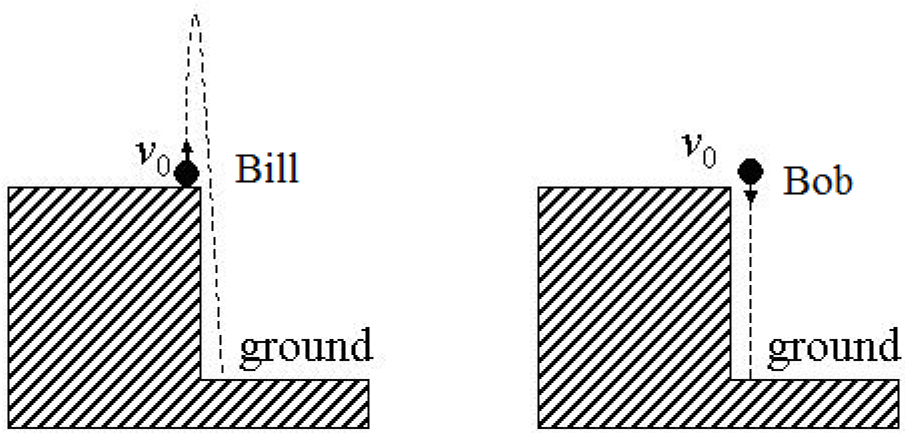
INTERVIEW PROBLEMS FOR CONTROL CONDITION

PROBLEM 1 – ENERGY CONSERVATION

Adapted from Singh and Rosengrant (2003)

You and your friends are standing atop a hill and are practicing firing a rifle. Bill likes to shoot straight up in the air, while Bob prefers to shoot pointing downward. Even though they assume that air resistance is not a factor, yet they cannot decide how the speeds at which the bullets will hit the target on the ground will compare in the two cases. Knowing that you are taking physics, so they ask you “Which one of our bullets will be travelling faster when it hits the target on the ground?”

What is your answer? Explain your reasoning.

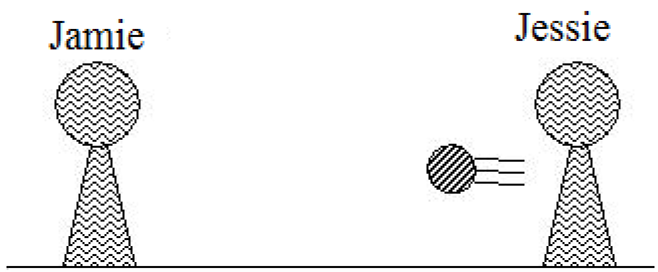


PROBLEM 2 – MOMENTUM CONSERVATION

Adapted from Singh and Rosengrant (2003)

You and your friends are trekking over a nearly frictionless frozen lake. At one point, when everyone is stationary, Jessie aims a ball toward Jamie. Knowing that you are taking physics, asks "If I threw this ball directly at Jamie, what would happen as a result?"

What is your answer? Explain your reasoning.



PROBLEM 3 – ROTATIONAL MOTION

Adapted from Rimoldini and Singh (2005)

You missed physics class one day and so you ask one of your friends to explain what went on in class. Your friend begins to describe a very interesting demo in which the instructor called on two volunteers. He gave each identical looking disks – one blue and one red -- and asked them each to grab a disk and turn it side to side – much like the motion one would make while rotating a steering wheel. The student who grabbed the blue disk could do that very easily, but the one who grabbed the red disk struggled. It was not because one student was stronger than the other, because when they exchanged the disks, again the student who grabbed the red disk had a harder time. Your friend recalled what happened, but did now know quite why that happened, so she asks "Was it because the red disk was made of a heaver material than the blue disk?"

What is your answer? Explain your reasoning.

PROBLEM 4 – ROTATIONAL MOTION

Adapted from Rimoldini and Singh (2005)

You and your friend see a person riding down the street on a penny-farthing bicycle shown below. Your friend asks, "At any instant, how does the linear velocity of the point at the top of the front wheel compare with the linear velocity of the top point of rear wheel?"

What is your answer? Explain your reasoning.

PROBLEM 5 – GRAVITATION, NEWTON'S III LAW

Modified from Hestenes et al. (1992)

You and your friend hear a news item about an asteroid the size of an airplane that came very close to the Earth on April 1 this year. Your friend asks. "Suppose this asteroid had been more massive, would it have been more, less or equally likely to collide with the Earth?"

What is your answer? Explain your reasoning.

APPENDIX K

INTERVIEW PROBLEMS FOR GUIDED CONSTRUCT CONDITION

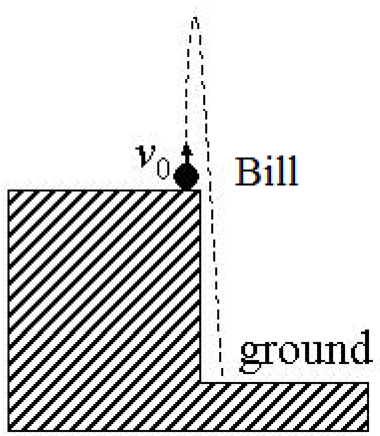
PROBLEM 1 – ENERGY CONSERVATION

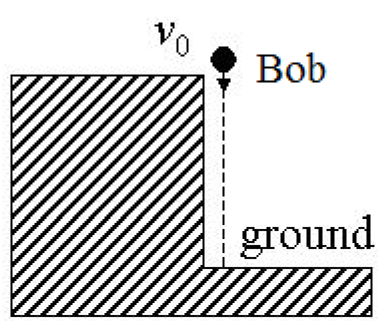
Adapted from Singh and Rosengrant (2003)

You and your friends are standing atop a hill and are practicing firing a rifle. Bill likes to shoot straight up in the air, while Bob prefers to shoot pointing downward. Even though they assume that air resistance is not a factor, yet they cannot decide how the speeds at which the bullets will hit the target on the ground will compare in the two cases. Knowing that you are taking physics, so they ask you "Which one of our bullets will be travelling faster when it hits the target on the ground?"

What is your answer?

- Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.
  HINT: In your argument, you may want to consider:
  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?





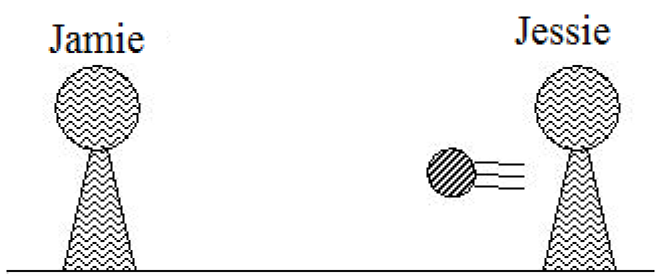
PROBLEM 2 – MOMENTUM CONSERVATION

Adapted from Singh and Rosengrant (2003)

You and your friends are trekking over a nearly frictionless frozen lake. At one point, when everyone is stationary, Jessie aims a ball toward Jamie. Knowing that you are taking physics, asks "If I threw this ball directly at Jamie, what would happen as a result?"

What is your answer?

- Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.
  HINT: In your argument, you may want to consider:
  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?



PROBLEM 3 – ROTATIONAL MOTION

Adapted from Rimoldini and Singh (2005)

You missed physics class one day and so you ask one of your friends to explain what went on in class. Your friend begins to describe a very interesting demo in which the instructor called on two volunteers. He gave each identical looking disks – one blue and one red -- and asked them each to grab a disk and turn it side to side – much like the motion one would make while rotating a steering wheel. The student who grabbed the blue disk could do that very easily, but the one who grabbed the red disk struggled. It was not because one student was stronger than the other, because when they exchanged the disks, again the student who grabbed the red disk had a harder time. Your friend recalled what happened, but did now know quite why that happened, so she asks "Was it because the red disk was made of a heaver material than the blue disk?"

What is your answer?

- Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.

  HINT: In your argument, you may want to consider:
  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?

PROBLEM 4 – ROTATIONAL MOTION

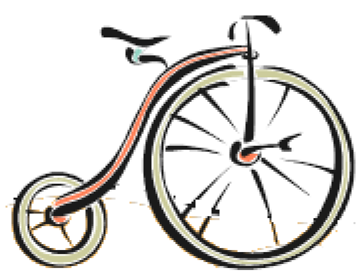
Adapted from Rimoldini and Singh (2005)

You and your friend see a person riding down the street on a penny-farthing bicycle shown below. Your friend asks, “At any instant, how does the linear velocity of the point at the top of the front wheel compare with the linear velocity of the top point of rear wheel?”

What is your answer?

- Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.

  HINT: In your argument, you may want to consider:
  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?



PROBLEM 5 – GRAVITATION, NEWTON'S III LAW

Modified from Hestenes et al. (2005)

You and your friend hear a news item about an asteroid the size of an airplane that came very close to the Earth on April 1 this year. Your friend asks. "Suppose this asteroid had been more massive, would it have been more, less or equally likely to collide with the Earth?"

What is your answer?

- Construct an argument to justify your conclusion. Explain your position clearly and completely by providing all reasons that supports your conclusion.

  HINT: In your argument, you may want to consider:

  - What evidence supports your reasons?
  - One of your classmates may disagree with your conclusion. What might they think is the alternative conclusion?
  - What reasons would your classmate provide to support their conclusion?
  - What would you reply to your classmate to explain that your position is right?

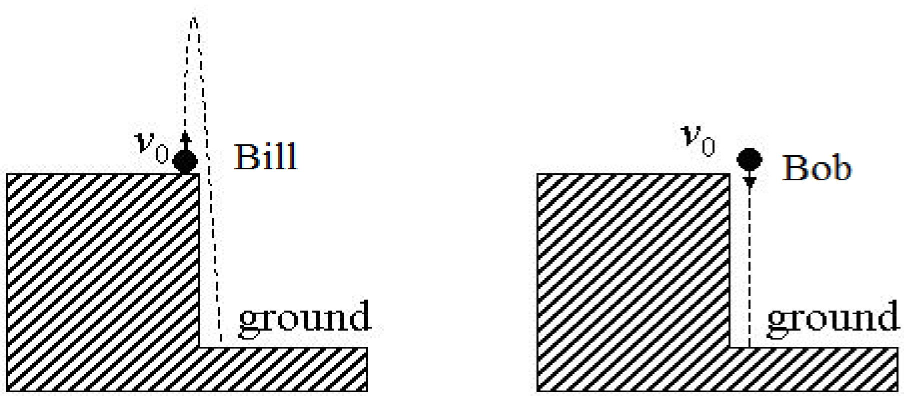
APPENDIX L

INTERVIEW PROBLEMS FOR GUIDED EVALUATE CONDITION

PROBLEM 1

Adapted from Singh and Rosengrant (2003)

You and your friends are standing atop a hill and are practicing firing a rifle. Bill likes to shoot straight up in the air, while Bob prefers to shoot pointing downward. They cannot decide how the speeds at which the bullet will hit the target on the ground will compare in the two cases. Knowing that you are taking physics, so they ask you to settle their argument.



Bill: "My bullet will hit the ground faster because my bullet will gain height and energy over a longer time, so it will hit the ground with greater energy, thus greater speed."

Bob: "Your bullet may rise higher, but it loses energy by working against gravity. My bullet does not have to work against gravity so it will hit the ground with greater speed."

Which one of them, Bill or Bob, do you agree with? Or do you have a different argument?

- Explain, elaborate, and justify your preferred solution.

  HINT: In your solution, you may want to consider:

  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?

- How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

PROBLEM 2

Adapted from Singh and Rosengrant (2003)

You and your friends are trekking over a nearly frictionless frozen lake. At one point, when everyone is stationary, Jessie aims a ball toward Jamie. The two of them argue about what will happen if Jessie threw the ball toward Jamie.

Jamie: "Nothing will happen to me. The ball will bounce off me elastically and not make me move in any way. Rather, throwing the ball will push you away from me."

Jessie: "No! I will not move, rather, the ball when it hits you will impart its motion to you and push you to move away from me."

Which one of them, Jamie or Jessie, do you agree with? Or do you have a different argument?

- Explain, elaborate, and justify your preferred solution.

  HINT: In your solution, you may want to consider:

  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
  - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

PROBLEM 3

Adapted from Rimoldini and Singh (2005)

You missed physics class one day and so you ask one of your friends to explain what went on in class. Your friend begins to describe a very interesting demo in which the instructor called on two volunteers. He gave each identical looking disks – one blue and one red -- and asked them each to grab a disk and turn it side to side – much like the motion one would make while rotating a steering wheel. The student who grabbed the blue disk could do that very easily, but the one who grabbed the red disk struggled. It was not because one student was stronger than the other, because when they exchanged the disks, again the student who grabbed the red disk had a harder time. Your friend recalled what happened, but did now know quite why that happened, so she asks "Was it because the red disk was made of a heaver material than the blue disk?"
Two of your friends begin to answer the question.

Jamie: "Yes, definitely, the red disk had a greater mass than the blue disk. The disks were identical in size, so the only difference in inertia is due to the different materials. The disk with the heavier material is harder to turn."

Jessie: "No, I bet the materials were the same for both. In fact, the disks were both hollow, but the red one was stuffed with material toward the rim and the blue one had the same material stuffed toward the center."

Which one of them, Jamie or Jessie, do you agree with? Or do you have a different argument?

- Explain, elaborate, and justify your preferred solution.
  HINT: In your solution, you may want to consider:
  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
  - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

PROBLEM 4

Adapted from Rimoldini and Singh (2005)

You and your friend see a person riding down the street on a penny-farthing bicycle shown below. Your friend asks, “At any instant, how does the linear velocity of the point at the top of the front wheel compare with the linear velocity of the top point of rear wheel?” Two other friends jump in to answer.

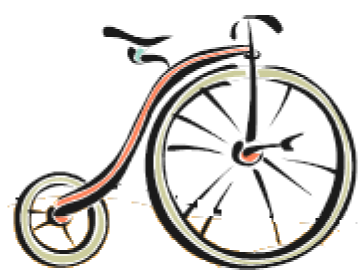
Bill: “The top point on the front wheel definitely has a larger linear velocity, because the front wheel has a larger radius and linear velocity is angular velocity times radius.”

Bob: “No, in fact the top point of the rear wheel has a larger linear velocity, because it is smaller and makes more than one rotation for every single rotation of the larger wheel to keep up.”

Which one of them, Bill or Bob, do you agree with? Or do you have a different argument?

- Explain, elaborate, and justify your preferred solution.

  HINT: In your solution, you may want to consider:
  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
  - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?



PROBLEM 5

Modified from Hestenes et al. (1992)

You and your friend hear a news item about an asteroid the size of an airplane that came very close to the Earth on April 1 this year. Your friend asks. “Suppose this asteroid had been more massive, would it have been more, less or equally likely to collide with the Earth?” Two other friends jump in to answer.

Jamie: “Yes, if the asteroid were more massive, it would definitely be more likely to hit the Earth, because it would experience a greater gravitational attraction force due to the Earth.”

Jessie: “Not so, if the asteroid were more massive it would have greater momentum and inertia, which means it would be harder for the Earth’s gravitational attraction force to move it closer to it.”

Which one of them, Jamie or Jesse, do you agree with? Or do you have a different argument?

➢ Explain, elaborate, and justify your preferred solution.
  HINT: In your solution, you may want to consider:
  - What evidence and reasons supports your selection?
  - Explain your reasoning for not choosing the alternative solution(s). What are the weaknesses in the alternative argument(s)?
  - How might a classmate supporting the other solution disagree with your preferred solution and how would you respond to them?

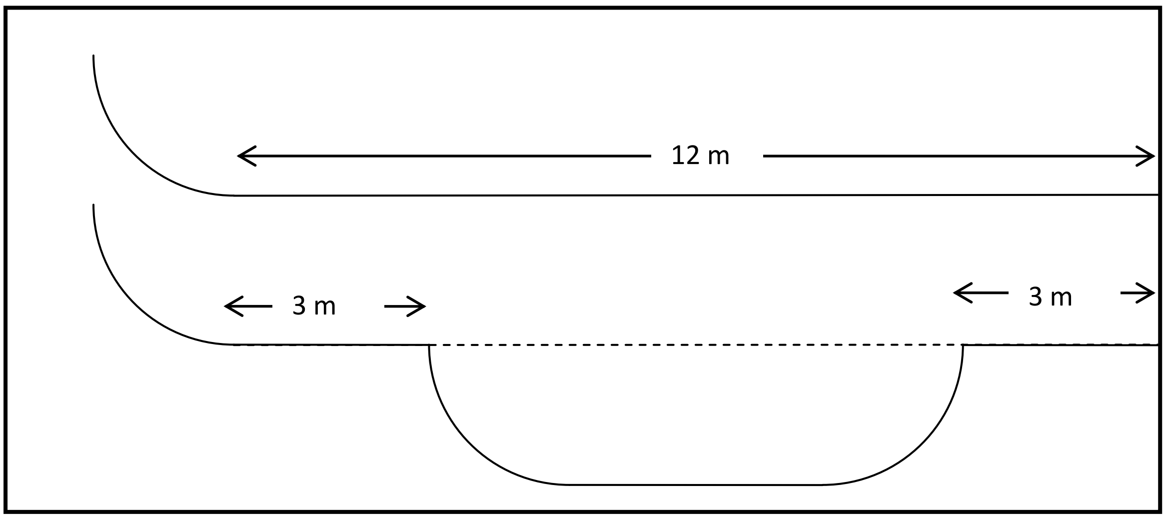
APPENDIX M

OPEN-ENDED PROBLEM FOR FIRST EXAMINATION

OPEN-ENDED PROBLEM - KINEMATICS

Adapted from Thaden-Koch et al. (2006)

You and your friend are roller boarding in a nearby park on two adjacent tracks. The tracks are identical except that one of them has a dip in it, but then rises up to the same level as the other track as shown in the picture. You know that if you choose the second track, the dip in the track typically makes your roller board speed up by 2 m/s from its speed before hitting the dip, but then when it goes back up to the top it slows back down again to the same speed as it was before hitting the dip. Your friend insists that the two of you race and asks "Will one of us win and if so by how much, or will we just come out even?"



What is your answer? Explain your reasoning.

APPENDIX N

PROBLEM SOLVING STATEGIES FOR EACH ARGUMENATIVE PROBLEM

BY EACH CASE STUDY PARTICIPANT

PROBLEM SOLVING STATEGIES EMPLOYED BY EACH PARTICIPTANT ON AN OPEN-ENDED PROBLEM TO ASSESS STATEGIES PRIOR TO RECEIVING ARGUMENATIVE PROBLEMS

Case Condition	Problem 1 (From First Examination) – Kinematics
Control	
Adan	PM and PA
Amber	PM
Alfred	HPC
Abby	PM and CR
Guided Construct	
Blake	PA
Blaise	PM
Brice	PM
Bailey	PM
Guided Evaluate	
Cedric	PM
Cayden	PM
Carson	PM and CR
Callie	PM

Note. CCS = Construct and Compare Solutions; Co = Covariational Reasoning; CR = Case Reuse; ECT = Extreme Case Thought Experiment; EPC = Evaluate Problem Cases; HPC = Hypothetical Plug-and-Chug; MMM = Mapping Meaning to Mathematics; PA = Pictorial Analysis; PM = Physical Mechanism; QCA = Qualitative Concept Application; RCT =Recursive Concept Testing; RPC = Recursive Plug-and-Chug

PROBLEM SOLVING STATEGIES EMPLOYED BY EACH PARTICIPTANT FOR HOMEWORK PROBLEMS

Case Condition	Problem 1 – Work and Kinetic Energy	Problem 2 – Energy Conservation	Problem 3 – Momentum Conservation	Problem 4 – Momentum and Impulse	Problem 5 – Gravitation, Newton's III Law
Control					
Adan	CO	QCA and CR	CR and PM	RCT	PM
Amber	CO	CR and CO	PM	CO	QCA
Alfred	CO	PM	PM	PM	CO
Abby	CR	CR and PM	CR	CO	CO
Guided Construct					
Blake	CO and QCA	CO and PM	CO	QCA	CO
Blaise	CO	QAC	MMM	QCA	QCA
Brice	HPC	HPC	CR	PM	QCA
Bailey	CO	CR and PM	PM	PM	PM
Guided Evaluate					
Cedric	CCS and CO	QCA	CCS and QCA	CO	CCS and QCA
Cayden	EPC, CO, CR, and ECT	EPC and QCA	QCA	CCS and QCA	EPC and QCA
Carson	CCS, QCA and CO	CCS and CO	CCS, CR, and PM	CCS and PM	CCS and PM
Callie	CCS and CO	PM	PM	CCS and PM	EPC and PM

Note. CCS = Construct and Compare Solutions; Co = Covariational Reasoning; CR = Case Reuse; ECT = Extreme Case Thought Experiment; EPC = Evaluate Problem Cases; HPC = Hypothetical Plug-and-Chug; MMM = Mapping Meaning to Mathematics; PA = Pictorial Analysis; PM = Physical Mechanism; QCA = Qualitative Concept Application; RCT =Recursive Concept Testing; RPC = Recursive Plug-and-Chug

PROBLEM SOLVING STATEGIES EMPLOYED BY EACH PARTICIPTANT FOR INTERVIEW PROBLEMS

Case Condition	Problem 1 – Energy Conservation	Problem 2 – Momentum Conservation	Problem 3 – Rotational Motion	Problem 4 – Rotational Motion	Problem 5 – Gravitation, Newton's III Law
Control					
Adan	RCT and PA	CO	QCA	CR	PA and PM
Amber	PM	CR and PM	CO	CR and PM	CO
Alfred	PM	PM	PM	PM	PM
Abby	PM	CR	CR and PM	PM	PM
Guided Construct					
Blake	CO	PM	QCA	PM	CO
Blaise	QCA	QAC and ECT	QCA	QCA	CO
Brice	HPC	PM	QCA	CO	HPC
Bailey	PM	CR and PM	PM	CR	PM
Guided Evaluate					
Cedric	EPC and PA	CCS and ECT	CCS and PM	EPC, PA, and QCA	EPC and PM
Cayden	CCS and QCA	EPC and PM	CCS and QCA	CCS, PM, and CO	CCS and CO
Carson	PM	CCS and PM	EPC and ECT	CR	CCS and PM
Callie	EPC and PM	CCS, CR, and PM	EPC and PM	EPC and PM	PM

Note. CCS = Construct and Compare Solutions; Co = Covariational Reasoning; CR = Case Reuse; ECT = Extreme Case Thought Experiment; EPC = Evaluate Problem Cases; HPC = Hypothetical Plug-and-Chug; MMM = Mapping Meaning to Mathematics; PA = Pictorial Analysis; PM = Physical Mechanism; QCA = Qualitative Concept Application; RCT =Recursive Concept Testing; RPC = Recursive Plug-and-Chug

APPENDIX O

DATA COLLECTION MATRIX

DATA COLLECTION MATRIX

Overarching research question: What patterns of undergraduates' argumentation quality, conceptual quality of problem solutions, epistemology, and problem solving strategies can emerge in introductory physics across multiple topics?

Research Questions	Force Motion Concept Evaluation (FMCE)	Interviews	Written Artifacts – Problem Sets
How do undergraduate introductory physics students solve physics problems supporting alternative forms of argumentation?	S	P	P
What problem solving strategies do students uses to solve problem incorporating construction or evaluation of arguments in physics?	S	P	P
In what ways are students' problem solving strategies for argumentation problems formats similar to or differ from traditional "explain your reasoning" problem formats?	S	P	P

P = Primary data source used to answer research questions; S = Secondary or supporting data sources used to answer research questions.

VITA

Carina M. Rebello completed her B.S. in Physics at Kansas State University in 2005. She continued her academic work at Ball State University earning a M. S. in Physics in 2007. Her Masters research was on the topic of medical physics. After completing her M.S., Ms. Rebello completed graduate coursework and research in physics at Indiana University Purdue University in Indianapolis and in the Physics Department at University of Missouri.

In August 2009, Ms. Rebello began her graduate work in the MU Science Education Program to pursue a Ph.D. in Learning, Teaching, and Curriculum. In addition to completing her coursework, Ms. Rebello completed research on projects including development and implementation of assessments in biotechnology, facilitating high teachers to implement the Physics First curriculum in their high school classrooms, and investigating use of mathematics in physics. Ms. Rebello presented her work at national and international conferences. She also published her work in several peer-reviewed journal publications

Ms. Rebello's dissertation research focuses on argumentative problems in introductory physics. Using a two-phase concurrent mixed methods design, she investigated the impact of argumentation prompts on the quality of physics problem solutions to problems where students had to either construct or evaluate arguments. Results showed that the prompts improve the conceptual and argumentation quality of students' solutions to physics problems. Further, the intervention showed promise for addressing the gender gap in physcics.