INTRODUCTORY PHYSICS STUDENTS' PHYSICS AND MATHEMATICS EPISTEMOLOGIES

by

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ABSTRACT

The purpose of this three study dissertation is to investigate why students are enrolled in introductory physics courses experience difficulties in being successful; one possible source of their difficulties is related to their epistemology. In order to investigate students' epistemologies about mathematics and physics, students were observed solving physics problems in groups during a laboratory course (study 1) and while solving physics and mathematics problems individually during office-hour sessions (study 2). The Epistemological Resources theoretical framework was employed (Hammer & Elby, 2002).

Using emergent and a priori epistemological resource operationalizations (Jones, 2015), 25 distinct epistemological resources were identified in study 1. Differences in physics epistemological resource usage between students of varying academic background (as measured by their number of previously completed mathematics and science classes were identified.

By employing an external (Jones, 2015) and internal (Scanlon, 2016) a priori epistemological resource coding scheme, a total of 17 distinct epistemological resources were identified in study 2. The data were sampled to compare the mathematics and physics epistemological resource usage of participants with consistent and inconsistent sign usage in an energy conservation physics problem in order to provide a meaningful context for discussion. Participants of the same sign usage group employed epistemological resources similarly. Conversely, participants in different groups had significantly different physics epistemological resource usage patterns.

Finally, student epistemological resource usage patterns from the first two studies were compared to course outcomes in order to determine implications for practice (study 3). Educators must be aware of and address the epistemological underpinnings of students' difficulties in introductory physics courses.

I. INTRODUCTION

Physics and mathematics are intrinsically intertwined (Arnol'd, 1999). Therefore, in order for students to be successful in a physics course, they must be able to use mathematics and physics knowledge and skills simultaneously. The extant literature proposes multiple factors that may contribute to students being unsuccessful in introductory physics courses such as issues related to aligning identity with goals of the course (French & Krause, 2006), stereotype threat (Kost-Smith et al., 2010), lack of motivation (Eryilmaz, Yildiz, & Akin, 2010), and lack of academic preparation (Halloun & Hestenes, 1985). One challenge in increasing the number of qualified STEM professionals is that most STEM degree plans require students to take at least one introductory physics course whether it be conceptual, algebra-based, or calculus-based (Beichner, 2012). Introductory physics courses have some of the DFW rates (percentage of students that earn a D, F, or withdraw from a course) across all courses at the undergraduate level reaching as high as 50% (e.g., Escoe & Patchell, 2013; "A Closer Look", 2014). If the students initially interested in STEM are unable to pass these gateway introductory physics courses, they are also unable to complete their intended STEM degree. Therefore, in order to produce more people qualified in STEM, research must be focused on how to help students enrolled in STEM pathways be successful in their introductory physics courses in order to matriculate through their degree plans. This dissertation focuses on investigating a possible reason why students are not successful in introductory physics courses.

There are a myriad of reasons why students experience difficulties with passing introductory physics courses. Over the last 50 years, there have been multiple studies investigating particular reasons why so many students do not pass introductory physics courses. A few of the reasons for the high DFW rates in introductory physics are students' lack of mathematics preparation and skill (see Hudson & McIntire, 1977; Hudson & Liberman, 1982; Meltzer, 2002; Tuminaro & Redish, 2003; Buick, 2007), difficulties working with symbolic notation (Torigoe & Gladding, 2011), epistemological conceptions that differ from the instructors' and courses' (Lising & Elby, 2004; Franco et al., 2012), gender biases in the courses (Lorenzo, Crouch, & Mazur, 2006; Kost, Pollock, & Finkelstein, 2007), and course pedagogy and structure (Elby, 2001; Lorenzo et al., 2006). Of particular interest in this study is how students' epistemologies about physics and mathematics shape students' thoughts about and perceptions of physics and mathematics and the cognitive blending of the two disciplines (Bing & Redish, 2007).

This dissertation specifically focuses on the intersection of students' epistemologies about physics and their epistemologies about mathematics. The purpose of this phenomenological dissertation is to describe and characterize introductory algebra-based physics students' epistemologies about physics and mathematics using the Epistemological Resources theoretical framework (Hammer & Elby, 2001). Although there is no unified definition of epistemological resources, there are several salient features across descriptions. One of these features is that epistemological resource activation is highly context-dependent and is shaped through experience (see the Literature Review chapter for more information about epistemological resources).

The long-term goal of this line of inquiry is to determine the epistemological underpinnings of students' difficulties in physics courses. Once these epistemological underpinnings are understood, researchers can develop interventions to address inappropriate epistemological resource activation such that students can reach their educational goals.

Developmental education is a field of study that addresses how to help students be successful and reach their educational goals. A broad purpose of developmental education is to help all students achieve their post-secondary educational and personal goals by supporting them in and out of the classroom by adding to their existing skills and knowledge. Therefore, this dissertation falls under the purview of developmental education because it aims to investigate underlying reasons why some introductory physics students are unsuccessful in introductory physics courses.

Definitions of Key Concepts and Terms

In general, epistemology is the nature, source, and justification of knowledge (Hofer & Pintrich, 1997). While many epistemology theoretical frameworks describe epistemology as relatively coarse-grained, this study was framed using a finer-grained framework, specifically the Epistemological Resources theoretical framework (Hammer & Elby, 2000; see the Chapter II for more information about this framework). An example of an epistemological resource is Knowledge as Free Creation. This relates to the conception that knowledge can be freely created; for example, a child justifying their answer by saying “I made it up”. This epistemological resource relates to the source of knowledge and therefore describes the person’s underlying epistemology. Examples of other epistemological resources be discussed later in this dissertation. At this point, a few operationalized definitions to be used throughout this paper will be introduced.

Epistemology. Epistemology is the largest grain-sized of the constructs discussed. In general, it is a person's beliefs, conceptions, and ideas about the nature, source and justification of knowledge (Hofer & Pintrich, 1997). It is the ideas people have about knowledge.

Physics and Mathematics Epistemology. Physics epistemology and mathematics epistemology refer to the general ideas, conceptions, and beliefs about physics and mathematics held by practitioners of the discipline (Hofer & Pintrich, 1997). These two terms refer to the broad epistemologies of the two disciplines held by the broader physics and mathematics communities as a whole.

Epistemology about Physics and Mathematics. Epistemology about physics and epistemology about mathematics are the specific ideas, conceptions, and beliefs held by individual students about physics and mathematics. These two terms refer to the specific epistemologies of the physics and mathematics held by individuals.

Epistemological Resources. Epistemological resources are fine-grained pieces of cognitive structure that people subconsciously employ as they identify salient features in a set of circumstances (Hammer & Elby, 2000). This term refers to the broad range of epistemological resources that are employed in a wide variety circumstances. This term will be commonly used in this dissertation because the same epistemological resources can be employed across disciplines.

Physics and Mathematics Epistemological Resources. Physics epistemological resources and mathematics epistemological resources are pieces of cognitive structure that subconsciously employ while solving physics and mathematics problems, respectively.

Organization of the Dissertation

This dissertation will not follow the traditional five-chapter format. Instead it is composed of an introduction chapter (Chapter I), a literature review chapter (Chapter II), three separate manuscripts in article format described below (Chapters III, IV, and V), and a conclusions chapter (Chapter VI). The three manuscripts will be submitted for publication in refereed journals in the field of physics education research.

Study 1: Math and Physics Epistemological Resource Usage. The first study was a pilot study that investigated the epistemologies about physics of students enrolled in introductory, algebra-based physics. The purpose of the study was to get a broad, macroscopic view of the breadth of physics epistemological resources employed by students in introductory physics courses while solving physics problems. The research questions guiding this inquiry were:

1) Which physics epistemological resources do physics students use, as deduced from their group discussion while solving physics problems?

2) What is the nature of physics students' physics epistemological resources and their usage patterns?

3) In what ways are physics students' physics epistemological resources and usage patterns similar and/or different?

Study 2: Epistemological Resource Usage Variations. The second study focused specifically on the intersection of students' epistemology about physics and their epistemology about mathematics. In order to investigate the differences in students' epistemology about mathematics and epistemology about physics, participants solved one mathematics and one physics problem during each of the three office-hour sessions. The participants worked the problems one-on-one with the primary researcher during office-hour sessions. The research questions guiding the second study were:

> 1) Which epistemological resources do introductory physics students employ and what are their epistemological resource usage patterns while solving physics and mathematics problems?
>
> 2) How do the epistemological resources introductory physics students, and their usage patterns, compare for physics problem solving and mathematics problem solving?

Study 3: Epistemological Resources in the Physics Classroom. Finally, the third study focused on determining the implications of the first two studies for classroom practice. The relationships between students' physics and mathematics epistemological resources identified during physics and mathematics problem-solving and their course outcomes were identified (e.g., course grade, conceptual learning, attitudes and beliefs shifts). The research question guiding the third study was:

> What are the relationships between students' physics and mathematics epistemological resource usage and course outcomes?

Summary

The purpose of this chapter was to introduce the focus of this dissertation study, namely investigating the epistemological underpinnings of students' difficulties in introductory physics courses. First, the boundaries of the problem that the dissertation work studied were defined along with a brief discussion of the salient prior work. In order to set the stage and guide the reader, a list of epistemology key terms were defined including physics epistemology, epistemology about physics, epistemological resources, and physics epistemological resources.

Finally, the organization of the dissertation was explicated because this dissertation does not follow the traditional five-chapter layout. Instead this study is composed of an introduction, literature review, three manuscripts for publications, and a conclusion. Then, the research questions for each of the three studies were introduced.

II. LITERATURE REVIEW

The disciplines of physics and mathematics are intrinsically intertwined (Arnol'd, 1999). Therefore, in order for students to be successful in a physics course, they must be able to use mathematics and physics simultaneously. Previous research found that students may be unsuccessful in introductory physics courses because they lack the mathematics knowledge and skills necessary in order to understand physics (Hudson & McIntire, 1977; Hudson & Liberman, 1982; Meltzer, 2002; Tuminaro & Redish, 2003; Buick, 2007; Hubisz, 2009; Chediak, 2010). However even the most mathematically prepared students may still have difficulties in introductory physics courses—Tuminaro and Redish (2005) hypothesize this may be an issue related to how students use their mathematics knowledge in a physics context. Due to the different classroom environments in which students typically learn mathematics and science, they may conceive of knowledge differently in these two disciplines. These differing conceptions of knowledge implies a difference in epistemology. This chapter will focus on presenting the relevant research about the relationship between physics and mathematics, epistemology theoretical frameworks, students' epistemology about physics, and students' epistemology about mathematics.

Relationship between Physics and Mathematics

Throughout the literature, there are many conceptions about the relationship between physics and mathematics. Arnol'd (1999) states that "mathematics is a part of physics" solely because they are both experimental sciences (p. 1216). Others claim that mathematics is a tool for physics (Dormert, Airey, Linder, & Kung, 2007). Still others describe mathematics and physics as intrinsically woven together as inseparable components that allow for the making of meaning about the world around us (Pereira de Ataíde & Greca, 2013).

Pereira de Ataíde and Greca discussed mathematics and physics as intrinsically intertwined disciplines, with one driving innovations in the other and vice versa (2013). Throughout history there have been three main conceptions of the relationship between physics and mathematics: 1) mathematics used as an analogy for the physical world, 2) mathematics as the language of physics, and 3) mathematics is intrinsically linked to the construction of physics concepts and ideas (Pereira de Ataíde & Greca, 2013). This conceptualization supports the idea that many physicists view mathematics and physics as intimately intertwined**.** This implies that in order to be successful in any physics venture, one must be fluent in and knowledgeable about mathematics. Therefore, introductory physics students must learn how to apply the mathematics knowledge gained in their prior mathematics courses in a new physics context appropriately in order to “do” physics. The inability of students to make this application is commonly voiced by physics instructors teaching at the high school through graduate levels (Pereira de Ataíde & Greca, 2013).

In this dissertation, the relationship between mathematics and physics is defined similarly to Pereira de Ataíde and Greca’s (2013) third notion that physics and mathematics are intrinsically linked. That is, in order to fully understand either, one must understand both. However, there is a difference between mathematics as described by a mathematician and the mathematics described by a physicist. A sample problem that highlights the difference between how a physicist and a mathematician may interpret and use mathematics in their problem-solving is called Corinne's Shibboleth (Redish & Kuo, 2015) and it is shown below:

> One of your colleagues is measuring the temperature of a plate of metal placed above an outlet pipe that emits cool air. The result can be well described in Cartesian coordinates by the function: $T(x, y) = k(x^2 + y^2)$ where k is a constant. If you were asked to give the following function, what would you write for: $T(r, \theta)$ =? (2015, p. 3)

Redish and Kuo (2015) argue that typically when mathematicians look at this problem they would see two decontextualized variables (e.g., x and y) that have no relationship to the real world. They would also see the new variables (e.g., r and θ) as decontextualized variables. Therefore, they would just replace the old variables with the new variables, which would yield $T(r, \theta) = k(r^2 + \theta^2)$. Because variables are operationalized independent of the real-world context calling the variables x and y or r and θ has no difference in meaning and therefore can be interchanged.

On the other hand, when physicists look at this problem they identify x and y are defined as Cartesian coordinates which have meaning in the real world (e.g., these are spatial coordinates). The variables r and θ also have conventional meaning imparted on them that is physically significantly different than x and y (e.g., r and θ are polar coordinates, which are different spatial coordinates than y and x). Therefore, instead of seeing the variables as interchangeable like a mathematician, a physicist would impart meaning on the variables and use a coordinate transformation (namely $x = r \cos \theta$ and $y = r \sin \theta$) to rewrite the equation as $T(r, \theta) = kr^2$. The important thing to notice is that the assumptions leading to the answers given by a mathematicians and a physicist are often different. Different epistemologies related to meaning of variables led to different interpretations and therefore different answers (Redish & Kuo, 2015). Even more confusing for students and experts alike is that both answers are accepted as correct in each discipline but are qualitatively and quantitatively different. This is one possible reason why students have difficulties using the mathematics knowledge from a mathematics course because it is qualitatively different than mathematics used in physics. Their knowledge is framed by a different epistemology. This dissertation focuses on the mathematics used by physicists that introductory physics students are expected to know and be able to use in physical contexts. It is hypothesized that the difference between mathematics from mathematics courses and mathematics required for physics has an epistemological underpinning. Next, is a brief review of the salient and seminal epistemological theoretical frameworks.

Historical Perspectives of Epistemology

Throughout the literature there are multitudes of definitions and theoretical frameworks that describe personal epistemology. A few of these frameworks are Perry's Scheme of Intellectual and Ethical Development (1970), Women's Way of Knowing (Belenky, Clinchy, Goldberger, & Tarule, 1986), Epistemological Reflection Model (Baxter Magolda, 1992), Reflective Judgment Model (King & Kitchener, 1994), Argumentative Reasoning (Kuhn, 1991), Epistemological Beliefs (Schommer, 1990), and Epistemological Resources (Hammer & Elby, 2000). This section provides a brief historical perspective and a review of the epistemological theoretical frameworks relevant to physics and mathematics.

Hofer and Pintrich (1997) define epistemology as “an area of philosophy concerned with the nature and justification of human knowledge.” Epistemology as defined by Schommer (1990) is “what students believe about the nature of knowledge and learning." Redish (2010) simply defines epistemology as “what is accepted as evidence for believing a particular result.” These definitions are colored by the authors’ perspectives and disciplines. Along with each theoretical framework comes another definition and operationalization of epistemology.

One of the first instances in which epistemology appeared in the literature is Perry's seminal paper Forms of Intellectual and Ethical Development in the College Years: A Scheme (1970). Perry developed a stage, developmental model of epistemology containing nine “positions” that describe how students view the nature of and source of knowledge (Perry, 1970). The nine positions are aggregated into four categories: dualism, multiplicity, relativism, and commitment within relativism. These represent hierarchical structures students can transition between as they experience cognitive disequilibrium through experiences that broaden their understanding of the world (Perry, 1970).

The generalizability of Perry’s study was limited due to the sample population being comprised almost exclusively of middle to upper class White males attending Harvard University (Perry, 1970). In response to Perry’s study, Belenky et al. (1986) developed the Women's Way of Knowing framework to describe women’s epistemology and their ways of knowing and understanding the world. This model is a non-stage, developmental scheme that describes themes of knowing and understanding particular to women (Belenky et al., 1986). Women's Way of Knowing is comprised of five ways that women “know and view their world”: silence, received knowledge, subjective knowledge, procedural knowledge, and constructed knowledge. The ways of knowing are not stages (non-hierarchical) but are possibly developmental (i.e., change through time; Belenky et al., 1986).

Starting from Perry's and Belenky et al.'s models, Baxter Magolda began searching for gender-related implications of epistemology in the late 1980s. Through a five-year longitudinal study, Baxter Magolda (1992) developed the Epistemological Reflection Model, which contains four qualitatively different epistemological assumptions. The epistemic assumptions correlate with four stages: absolute, transitional, independent, and contextual knowing which describe how students view knowledge. These stages are developmental (Baxter Magolda, 1992).

The majority of the early research involving student epistemology were qualitative and tended to be time intensive in nature in order to determine each student's personal epistemologies (Hofer & Pintrich, 1997). Also, most of theoretical frameworks assumed that student epistemologies were unidimensional and were developmental (Hofer & Pintrich, 1997). Schommer (1990) developed a scheme of epistemology that was composed of four independent dimensions along with a quantitative measure of epistemology. The dimensions of epistemology, called Epistemological Beliefs, are fixed ability (intelligence as either a fixed entity or as incremental entity that can be improved), quick learning (learning should either happen quickly or can occur of over a long period of time), simple knowledge (knowledge is composed of either isolated bits or as highly interrelated concepts), and certain knowledge (either all knowledge can be known or uncertainty always exists; Schommer, 1990). Schommer developed a Likert-style questionnaire that probes students' epistemological beliefs along each dimension. The questionnaire allowed for a more quantitative approach to determining student epistemologies as well as the ability to quickly and efficiently measure the epistemological beliefs of large groups of students (Hofer & Pintrich, 1997). One drawback is that the questionnaire is context free; the questions do not reference specific disciplines or contexts for the answerer to keep in mind. Previous work has shown that students' epistemologies have both a domain-specific (e.g., varying across contexts) and domain-general (e.g., stable across contexts) components of epistemology (Muis, Bendixen, & Haerle, 2006). Therefore, the context-free nature of these epistemological questionnaires that students' responses may have varied depending on the context they had in mind while answering the questions (Pajares, 1992).

Theoretical Framework

The theoretical framework employed for this study is the Epistemological Resources framework in which students' epistemologies are described at a finer grain-size (Hammer & Elby, 2000). This framework describes student epistemology not as relatively stable beliefs but instead as independent pieces of cognitive structures called resources. Hammer and Elby (2001) describe epistemological resources as "cognitive building blocks from which students construct their epistemological views" (p. 564). One aspect of epistemology is the source of knowledge. Hammer and Elby (2002) discussed an epistemological resource, namely Knowledge as Propagated Stuff, which is a resource related to the source of knowledge. Specifically, Knowledge as Propagated Stuff describes the conception that knowledge can be passed from person to person.

Resources are activated or inhibited in patterns that are formed through experience (Hammer & Elby, 2000). In this framework, the aim of instruction is not to change students' beliefs (e.g., misconceptions about physics) but instead to train students to activate useful resources at appropriate times (Hammer & Elby, 2000). Epistemological resources are not conceived as 'expert' or 'novice'. Rather, there are appropriate and less appropriate times to activate particular resources (Hammer & Elby, 2002). This dissertation is framed with the Epistemological Resources theoretical framework and seeks to extend on the epistemological resource literature by investigating students' mathematics epistemological resources and physics epistemological resources.

Throughout the literature are many examples of how student epistemology about physics affects their physics learning. Student epistemology has been shown to affect how students learn in a physics course (Lising & Elby, 2004), as well as their conceptual learning gains (May & Etkina, 2002), grade point average (Schommer, 1993), problem-solving (Hammer 1994), and course retention (Perkins, Adams, Pollock, Finkelstein, & Wieman, 2004). This research led to efforts to reform introductory physics curriculum to include a discussion of and sometimes focus on epistemology (Otero & Gray, 2007; Redish & Hammer, 2009). More research into the interaction between students' epistemologies about physics and mathematics and their physics course performance is required in the future due to the dearth of research in this area.

Context-Dependent Nature of Epistemology

A large portion of the epistemology literature revolves around whether or not students' epistemologies are domain-general or domain-specific (Hofer & Pintrich, 1997). The domain-general model of epistemology describes student epistemologies as constant and consistent among and across disparate disciplines. For example, if students' epistemologies are domain-general, then a student's belief about the source of knowledge in physics would be the same as their beliefs about the source of knowledge in social studies. Conversely, if students' epistemologies are domain-specific, then a student's epistemology would differ across academic disciplines (e.g., their epistemology about physics would be different than their epistemology about history).

Hofer (2000) found that first-year college students had some epistemologies that cut across disciplines and some epistemologies that differed by disciplines. This implies that students have both domain-general and domain-specific components of epistemologies. Muis, Bendixen, and Haerle (2006) conducted a meta-analysis of 19 studies investigating the domain-generality or domain-specificity of personal epistemology. The meta-analysis included studies using within- and between-subjects designs. Muis et al. (2006) used Biglan's classification of academic domains to differentiate between the academic disciplines. In this classification system, academic domains have two dimensions: either hard (e.g. biological sciences) or soft (e.g. humanities) and either pure (e.g. mathematics) or applied (e.g. economics). Physics and mathematics are both classified as hard and pure disciplines. All of the studies examined by Muis et al. (2006) included a comparison of students' epistemologies regarding disciplines on opposite sides of Biglan's two dimensions (e.g., comparing a hard, pure discipline with a soft, applied or soft, pure discipline). The authors found across all 19 studies that students' epistemological beliefs consisted of both domain-specific and domain-general epistemological components, consistent with previous research (Muis et al., 2006).

This dissertation further examines the domain-generality or domain-specificity of student epistemologies by investigating students' epistemologies about mathematics and physics separately and then comparing them. This will add to the literature by comparing students' epistemological resources of two disciplines with the same dimensions of Biglan's classification (Muis et al., 2006). The following two sections will discuss the literature about students' physics epistemology and mathematics epistemology.

Physics Epistemology

The physics education research (PER) community recently began investigating how students' epistemologies may affect their learning of physics (diSessa, 1993). In general, epistemological work in the PER community has focused on research conceptualized with the Epistemological Beliefs (Schommer, 1990) and Epistemological Resources (Hammer & Elby, 2001) frameworks. Next will be a discussion of the two commonly employed epistemology theoretical frameworks used by the PER community.

Epistemological Beliefs. Using the Epistemological Beliefs framework, many surveys similar to Schommer's (1990) questionnaire have been developed, including the Views About Science Survey (VASS; Halloun, 1997), Maryland Physics Expectations Survey (MPEX; Redish, Steinberg, & Saul, 1998), Epistemological Beliefs About Physical Science survey (EBAPS; White, Elby, Frederiksen & Schwarz, 1999), and the most widely used Colorado Learning Attitudes about Science Survey (CLASS; Adams, Perkins, Dubson, Finkelstein, & Wieman, 2005). All of these surveys measure students' attitudes and beliefs about the discipline of physics. For example, an item from the EBAPS is: "When it comes to understanding physics or chemistry, remembering facts isn't very important." This question probes students' beliefs about the structure of knowledge (White et al., 1999). Students typically respond on a five to seven point

Likert-style scale from strongly disagree to strongly agree or on a multiple-choice scale with sample conversations for which they determine with whom they most agree.

Many researchers in the PER community have used the Epistemological Beliefs surveys differently than Schommer's original application (Schommer, 1990; Slaughter, Bates, & Galloway, 2011). The CLASS, for example, is typically administered at the start and end of a course to observe changes in students' attitudes and beliefs about physics over the course of a single semester due to their enrollment and involvement in a physics course (Slaughter et al., 2011). These results are often interpreted to determine the effectiveness (or ineffectiveness) of course pedagogy reforms (Slaughter et al., 2011). These surveys give a coarse-grained indication of student epistemologies.

Epistemological Resources. Another epistemology theoretical framework employed in PER is the Epistemological Resources framework developed by Hammer and Elby (2000). They state: "Epistemology draws on these resources, activating them—sometimes appropriately, sometimes not—in a manner that is sensitive to context. Furthermore, students presumably possess epistemological resources that could help them learn physics, but activate them only in other contexts" (p. 4).

Similarly, Bing and Redish (2009) state:

> An epistemological resource is a cognitive modeling element. It represents a tightly bundled packet of information that, when activated by the mind, leads the individual to interpret the knowledge at hand in a certain light. But an epistemological resource is a control structure, not a concept; epistemological resources affect how students perceive the nature of the

> situation under current consideration and they control what conceptual resources are brought to bear. (p. 020108-3)

Although there is no unified definition of epistemological resources in the literature, there are several salient features across descriptions. A foundational component of the Epistemological Resources framework is that students unconsciously employ epistemological resources and switch between resources rapidly. Which resource a student activates (and conversely inhibits) at a given time is highly dependent upon the context perceived by the student, and the context perceived depends the student's prior experiences (Hammer & Elby, 2000). Studies using the Epistemological Resources framework are typically qualitative because of the fine-grained, context-dependent nature and quick temporal transitions from resource to resource. Currently, a quick and easy method of determining epistemological resource usage akin to Schommer's (1990) Likert style surveys does not exist. Instead, qualitative observations of students in authentic settings are required. For example, observations of a group of students solving an introductory physics problem can be used to determine the types of epistemological resources the students are applying under these circumstances (Redish, 2014). Patterns of students' activation and inhibition of epistemological resources has also become a related area of interest (e.g., Tuminaro & Redish, 2004). Throughout the literature there are numerous examples of researchers determining the epistemological resources usage of students as they solve problems (diSessa, Elby, & Hammer, 2002; Bing, 2008; Bing & Redish, 2009; Jones, 2015).

While there is no comprehensive list of epistemological resources in the literature, researchers have described a number of epistemological resources including Calculation, Physical Mapping, Invoking Authority, Math Consistency, Knowledge as Free Creation, Accumulation, Supporting Evidence, Analogical Reasoning, Attention to Novelty, Knowledge from Direct Observation, Causal Reasoning, Consistency, Contrasting Cases, Mechanistic Reasoning, Plausibility, Sense Making, and Invoking Authority (Hammer & Elby, 2002; Bing & Redish, 2009; Jones, 2015). Because there are a large number of epistemological resources students can employ, a few resources relevant to the current research will be discussed here as an example of how questions are asked and coded. In his dissertation, Bing (2008) asked introductory physics students about the equation of continuity for a fluid. Below is the specific wording of the question:

> In class, we derived the integral constraint that expressed the conservation of matter of a fluid: $-\frac{d}{dt}\int_t \ \rho d\tau = \int_{\delta\tau}(\rho\vec{v})\cdot d\vec{A}$. Suppose that ρ describes the concentration in a solvent of a chemical compound that could be created or destroyed by chemical reactions. Suppose also that the rate of creation (or destruction) of the compound per unit volume as a function of position at the point $\vec{r}$ at a time t is given by $Q(\vec{r},t)$. Q is defined to be positive when the compound is being created, negative when it is being destroyed. How would the equation have to be modified? Explain. (p. 56)

Here is an example of one student's discussion with the interviewer about the right-hand side of the equation from the problem statement (words in italics were actions conducted by the student):

Student: So that's equal to the amount of flux (*draws*) through the area, because when something escapes out of a volume, you can always tell how much has escaped by drawing an area around that volume and (*gestures to and around* *picture*) measuring how much is leaving that area. (*pauses to look at interviewer)*

Interviewer: Ok.

Student: So this is like a flux, and it's a similar (*writes "flux" up by equation)* principle to Gauss's Law, I think, E&M.

The student's response is an example of employing the Physical Mapping epistemological resource (Bing, 2008). Bing (2008) describes the Physical Mapping resource in this way "when physics students frame their math use as Physical Mapping, they support their arguments by pointing to the quality of fit between their mathematics and the physical situation at hand" (p. 48). When students employ this resource, they trust mathematics as a source of knowledge insofar as it reflects the physical world. In this particular example, the student argued the validity of the equation by relating the meaning of the integral over the surface area of the volume to the physical meaning of the integral (i.e., how much stuff has left the volume equaling the amount of stuff that crosses the boundary). Because the student argued the validity of the equation based on its relationship to the real world, the student was invoking the Physical Mapping epistemological resource. Notice that in the second segment of the students' response, the student did not use the same epistemological resource (Bing claims the resource the student was using is indeterminant; 2008). The important thing to notice is that the student does not use the same resource throughout their explanation, and that a small amount of time and intervention from the interviewer prompted the student to switch to employing another epistemological resource.

Knowledge as Free Creation (Hammer & Elby, 2000) is an epistemological resource used commonly used by children where they invent information. This epistemological resource relates to the larger epistemological question about the source of knowledge. For example, a child may invent an imaginary character, and their explanation for the information is “I made it up” (Hammer & Elby, 2000). The child views knowledge as something that can be freely created and that freely created knowledge is trustable. Typically, this resource is inhibited in adults and therefore is not typically employed in adulthood.

A commonly invoked epistemological resource by introductory physics students is Invoking Authority also touching on the source of knowledge epistemology (Bing & Redish, 2009). When this epistemological resource is employed, students trust information that comes from an authority source (e.g., teacher, textbook, and internet). Which sources count as authoritative depends on students’ prior experience. This epistemological resource can be seen in problem-solving when students quote a rule, cite the textbook, or justify their responses by saying something to the effect of “because the teacher told me so” (Bing & Redish, 2009).

These are only three of the many of epistemological resources that have been categorized in the literature. In order to describe and define the differences between students’ epistemologies about physics and epistemologies about mathematics, a fine-grained description of student epistemology afforded by the Epistemological Resources framework must be employed.

Mathematics Epistemology

The mathematics education community has also produced a multitude of research studies on the intersection students’ personal epistemology and mathematics (Muis, 2004). Among these are studies of students’ beliefs about the nature of mathematics

(Schoenfeld, 1985), beliefs about the self in a mathematical context (Kloosterman, Raymond, & Emenaker, 1996), beliefs about mathematics social contexts (Cobb, Yackel, & Wood, 1989), and beliefs in relation to mathematical text comprehension (Schommer, Crouse, & Rhodes, 1992). Mathematics education researchers typically have defined epistemology either as a metacognitive construct (Garofalo & Lester, 1985) or as an affective construct (McLeod, 1992).

Muis (2004) conducted a meta-analysis of 33 studies specifically focused on students' epistemological beliefs about mathematics. Most of these studies used Schommer's Epistemological Beliefs framework (1990) as a guiding conceptual model. All the studies showed significant relationships between students' mathematics epistemology and course outcomes such as motivation and academic achievement (Muis, 2004). Similar to further research physics epistemology, a finer-grained framework of epistemology is required to tease apart differences between students' epistemologies about physics and mathematics and to investigate the domain-generality or domain-specificity of these epistemologies. This dissertation aims to add to the literature base by expanding the epistemological resources research to include a study of students' mathematics epistemological resources due to the lack of these studies in the extant literature.

Physics, Mathematics, and Epistemology Research

The relationship between students' epistemology about physics and their epistemology about mathematics has seldom been examined in the literature. Pereira de Ataíde and Greca (2013) discussed how the relationship between mathematics and physics has developed throughout history but only hinted at the epistemological aspect of the relationship. The main finding of their study was that a “close relationship appears to exist between the way students solve the [physics] problems and the epistemic view that students hold of the role played by mathematics in physics” (Pereira de Ataíde & Greca, 2013, p. 1415). This supports the hypothesis that there may be a connection or significant disconnection between students’ epistemologies about physics and mathematics.

Liu and Liu (2011) interviewed a small group of mathematics and physics majors about their beliefs about mathematics, physics, and the relationship between the two disciplines in a between-subjects design. Six epistemological themes for each discipline were generated from the analysis of student discussions and responses. The themes for physics were tentativeness, authority, empirical nature, creativity and imagination, subjectivity versus objectivity, and social cultural aspect. Similarly, the themes for mathematics were certainty, logical nature, empirical nature, creativity, imagination, discovered versus invented, and social cultural aspects. The authors compared the responses of the physics students to the responses of the mathematics students and found the “physics group espoused similar epistemological beliefs of mathematics with those of the mathematics group, yet the mathematics group… demonstrated more naive beliefs of the nature of science/physics than their counterparts” (Liu & Liu, 2011). This suggests that there may be a relation between how introductory physics students view mathematics and physics. One drawback was that this study was a between-subjects design (e.g., mathematics student’s epistemology compared with physics student’s epistemologies rather than comparing the epistemologies about physics and mathematics of a single student) and was a study of physics majors, which does not generalize to other student populations. Because epistemology is highly dependent on context, experience, domain, and situation, a within-subjects comparison of student epistemologies about physics and mathematics is required in order to classify similarities and differences for each student.

One other study investigated pre-service teachers' epistemology about the relationship between mathematics and physics. The authors did not categorize the pre-service teachers' epistemologies they only categorized their understanding of the relationship between mathematics and physics (Al-Omari & Miqdadi, 2014).

Given that the above studies are the only extant literature on the relationship between mathematics, physics, and epistemology, there is a need for more research on this intersection. Specifically, there needs to be a study using a within-subjects design on the physics and mathematics epistemological resources students employ as they solve mathematics and physics problems. A comparison of the similarities and differences in epistemological resource usage should then be conducted. Current literature suggests that the differences among students' epistemology about mathematics and physics are nuanced and therefore require a finer-grained epistemology theoretical framework than the Epistemological Beliefs (Schommer, 1990) framework to tease out differences. Finally, research into how the relationship between students' epistemologies about mathematics and physics affect course outcomes will also be practical and applicable to a wider audience and will contribute to the effort to produce more STEM-qualified individuals in the United States.

Summary

The purpose of this chapter was to present relevant literature related to students' epistemologies about physics and mathematics. An argument for the need for this dissertation was woven into the discussion of previous research. The first literature reviewed was about the relationship between mathematics and physics. Because the dissertation focuses on students' use of mathematics in a physics context and their epistemologies about physics and mathematics, the relationship between mathematics and physics as defined by the literature is crucial.

Next, an overview of the major epistemology theoretical frameworks from the education literature base were presented. This discussion was presented chronologically. Then the epistemology theoretical frameworks typically employed in the physics education literature were discussed. Two major frameworks, Epistemological Beliefs (Schommer, 1990) and Epistemological Resources (Hammer & Elby, 2000), were compared and contrasted as well as related to the framework choice for this dissertation.

The previous research related to students' epistemology about mathematics was presented next. This included a discussion of how students' epistemology about mathematics affected their course outcomes. Finally, a review of the literature on the intersection of physics, mathematics, and epistemology was presented.

III. STUDY I: MATH AND PHYSICS EPISTEMOLOGICAL RESOURCE USAGE

Introduction

Most science, technology, engineering, and mathematics (STEM) degree plans in the United States require students to take at least one introductory physics course which have some of the highest drop-fail-withdraw (DFW) rates across all courses at the undergraduate level (Beichner, 2012). Typically, the DFW rates for introductory physics courses are between 15-50% (Mullenax, 2006). If the students interested in STEM cannot pass these gateway introductory physics courses or have negative classroom experiences, they will be unable to complete their intended STEM degree (Cleaves, 2005; Munro & Elsom, 2000; Ware, Steckler, & Leserman, 1985). Students losing interest in STEM would be counterproductive to the aim of increasing the number of STEM-qualified professionals in the United States as called for by multiple initiatives (Xue & Larson, 2015). Therefore, to produce more people qualified in STEM, research must focus on how to help STEM students be successful in introductory physics courses. This study will focus on the epistemological underpinnings of students' difficulties in introductory physics by examining the epistemological resource usage of these students (Hammer & Elby, 2000).

There are a myriad of reasons why students have difficulty passing introductory physics courses. Over the last 50 years there have been a plethora of studies investigating particular reasons why so many students do not pass introductory physics courses. A few of the reasons for the high DFW rates in introductory physics posited by the literature are students' lack of mathematics preparation and skill (Hudson & McIntire, 1977; Hudson

& Liberman, 1982; Meltzer, 2002; Tuminaro & Redish, 2003; Buick, 2007), difficulties working with symbolic notation (Torigoe & Gladding, 2011), epistemological conceptions that differ from the instructors' and courses' epistemological underpinnings (Lising & Elby, 2004; Franco et al., 2012), gender biases in the courses (Lorenzo et al., 2006; Kost et al., 2007), and course pedagogy and structure (Elby, 2001; Lorenzo et al., 2006). But even the most mathematically prepared students may still have difficulties in introductory physics courses—Tuminaro and Redish (2005) hypothesize this may be an issue related to how students use their mathematics knowledge in a physics context.

Of particular interest is how students' epistemologies of physics and mathematics shape their thoughts about and perceptions of physics and mathematics and the blending of the two disciplines (Bing & Redish, 2007). The purpose of this phenomenological study was to describe and characterize introductory algebra-based physics students' physics epistemology using the Epistemological Resources theoretical framework (Hammer & Elby, 2000). The research questions guiding this inquiry were:

1) Which physics epistemological resources do physics students use as deduced from their group discussion while solving physics problems?

2) What is the nature of physics students' physics epistemological resources and their usage patterns?

In general, the physics education research (PER) community has conducted research framed and conceptualized with the Epistemological Beliefs (Schommer, 1990) and Epistemological Resources (Hammer & Elby, 2000) frameworks. Using the Epistemological Beliefs framework, many surveys similar to Schommer's (1990) questionnaire have been developed; including the Views About Science Survey (VASS; Halloun, 1997), Maryland Physics Expectations Survey (MPEX; Redish et al., 1998), Epistemological Beliefs About Physical Science survey (EBAPS; White et al., 1999), and (the most widely used) Colorado Learning Attitudes about Science Survey (CLASS; Adams et al., 2005). Unfortunately, the Epistemological Beliefs framework does not provide a fine enough grain size to allow for comparisons of students' epistemology across similarly described disciplines (e.g., mathematics and physics).

In this study, epistemology is described using the Epistemological Resources framework developed by Hammer and Elby (2000). They state: "Epistemology draws on these resources, activating them—sometimes appropriately, sometimes not—in a manner that is sensitive to context. Furthermore, students presumably possess epistemological resources that could help them learn physics, but activate them only in other contexts" (p. 4).

Similarly, Bing and Redish (2009) state:

> An epistemological resource is a cognitive modeling element. It represents a tightly bundled packet of information that, when activated by the mind, leads the individual to interpret the knowledge at hand in a certain light. But an epistemological resource is a control structure, not a concept; epistemological resources affect how students perceive the nature of the situation under current consideration and they control what conceptual resources are brought to bear. (p. 020108-3)

The central theme throughout the descriptions of epistemological resources is that students have a toolbox of epistemological resources that they can draw upon to shape their thoughts about the nature, source, and justification of knowledge. While there is no unified definition of epistemological resources in the literature base, there are a few salient features across descriptions. A foundational component of the Epistemological Resources framework is that students employ epistemological resources subconsciously and can switch between epistemological resources rapidly. Which epistemological resources a student activates (and conversely inhibits) at a given time is highly dependent upon the context perceived by this student and this perceived context depends their previous experiences (Hammer & Elby, 2000). Studies that use the Epistemological Resources framework are typically qualitative in nature because students change resources rapidly and students do not have articulable access to the resources being employed. A quick and easy method of determining epistemological resource usage akin to Schommer's (1990) Likert style survey does not currently exist. Instead, qualitative observations of students in authentic settings are required. Throughout the literature there are numerous examples of researchers determining the epistemological resources usage of students as they solve problems (diSessa et al., 2002; Bing, 2008; Bing & Redish, 2009; Jones, 2015).

Methodology

The purpose of this phenomenological study was to investigate the physics epistemological resource usage of students that are enrolled in introductory physics courses. Audio recording data were collected while participants conducted a group think-aloud as they solved problems in an introductory physics laboratory course. The recordings were transcribed verbatim and these transcriptions were the main data source for the study. In order to determine the physics epistemological resources employed by participants, content analysis for both latent and manifest codes was conducted (Neuendorf, 2002; Downe-Wamboldt, 1992). The epistemological resources were first identified emergently and then by employing an a priori epistemological resource operationalization scheme (Jones, 2015).

Participants. The participants in this study were students enrolled in an introductory, algebra-based physics course designed for life-science students at a small, private, liberal arts university in Texas. Data were collected during a summer semester. Most students majoring in a non-physics science (e.g., biology, chemistry, kinesiology) take these courses because they required by their degree plans. Shown in Table 1 is the demographic information for each participant in this study. The last column is the group categorization based on the participants' number of mathematics and science courses previously completed (see the Sampling section for more information). A total of ten participants were included in the study.

Sampling. The physics course in which the participants were enrolled was the basis for the purposive sampling at the start of the study; in order to answer the research questions the participants must have been enrolled in an introductory physics course. Next, a convenience sample of the students that opted to participate were included as participants.

Table 1

Participant Demographic Information

Name	Age	Years in College	Number of Math Classes	Number of Science Classes	Group
Ana	22	3.5	2	5	L/L
Andrea	22	3	2	4	L/L
Brenda	21	3	2	7	L/H
Caitlin	20	2	3	10	H/H
Chris	20	2	3	11	H/H
Christina	19	1	1	8	L/H
Juanita	21	4	2	7	L/H
Rachel	30	6	1	5	L/L
Sofia	22	4	3	8	H/H
Thomas	19	2	1	0	L/L

After data collection, participants' data were sampled in order to show a meaningful cross-section of data collected. Maximum variation sampling was implemented with participant data grouped by the number of science and mathematics classes they have previously completed (Miles, Huberman, & Saldaña, 2014). The epistemological resources framework dictates that the number of previously completed mathematics and science courses will affect the physics epistemological resources employed by students because these courses have shaped their understandings of mathematics and physics knowledge (Hammer & Elby, 2000). The sampling yielded three groups; namely lower number of mathematics classes and a lower number of science classes group (L/L), lower number of mathematics classes and a higher number of science classes group (L/H) and a higher number of mathematics classes and a higher number of science classes group (H/H). The L/L group included four participants with zero to three mathematics class and zero to five science classes. The L/H group included three participants with zero to two mathematics classes but with six or more science classes. Finally, the H/H group included three participants with three or more mathematics classes and six or more science classes (see Table 1 for a listing of the participants in each group). There is not higher number of mathematics classes and a lower number of science classes group (H/L) because none of the participants of this study fell into this category.

For each of these groups, one participant was selected based on the quality of the audio recording and discussion (i.e., recording quality and the richness of the discussion). Problem-solving sessions were selected such that the chosen participant for each group worked with one other participant from each of the three groups (e.g., for a selected L/L participant, the problem-solving sessions were selected such that this participant worked with another L/L participant, a L/H participant, and a H/H participant). For each participant chosen, three problem-solving sessions were analyzed for a total of nine sessions with ten unique participants.

Data Source. The main data source for this study was verbatim transcripts of participants' group-work audio recordings. A total of nine problems were included in the sample set which included 129 pages of data between ten unique participants. At the end of each laboratory class period, participants were given a physics problem to solve and discuss in a group think-aloud format (see Appendix A for the problems participants solved in groups). The problems were chosen because they required the use of both mathematical and physical ideas and are typically difficult for students. These two conditions made them ripe for in-depth discussion. Participants recorded their discussion of the problems constituting a group think-aloud (Ericsson & Simon, 1993). The students were tasked with voicing all of their thoughts and to engage in a rich discussion. The purpose of this process was to observe the students solving problems in a real-life, authentic context because epistemological resource activation is highly context-dependent. Observing students solving problems in the actual context they typically would solve problems would more likely yield the "natural" epistemological resources used by the students.

Data Collection. The data were collected in two introductory, algebra-based physics courses, called physics 1 and physics 2, during a summer semester. After discussing the purpose and components of the study, the students were given the option to participate. All eligible participants opted to participate in the study for a total of unique 10 participants included in the analysis. The problems students solved were chosen such that a wide range of the types and difficulties of mathematics and physics required to solve each problem would be discussed by participants. Also, many of the problems covered topics that are traditionally difficult for students to solve correctly. The purpose of the study was to see the breadth of the physics epistemological resources employed by students when solving all types of physics problems.

Data Analysis. In order characterize the nature of participants' physics epistemological resources, a systematic qualitative analysis consisting of content analysis for latent and manifest codes was conducted (Neuendorf, 2002; Downe-Wamboldt, 1992). The data were analyzed in two phases. During the first phase, emergent coding aligned with the epistemological resource descriptions of Hammer and Elby (2000) and Bing and Redish (2009) was conducted to determine the physics epistemological resources employed by participants. This was done to ensure that the breadth and scope of physics epistemological resources employed by the students that were enrolled in introductory physics courses were identified. The verbatim transcripts were all coded twice during this phase, once in order to determine the emergent codes and operationalizations, and again to uniformly implement the emergent codes.

In the second phase, an a priori coding scheme from the literature was employed. The a priori coding scheme was developed by Jones (2015) while examining the physics epistemological resources employed by physics experts as they solved physics novel problems. The a priori coding scheme included 19 epistemological resources that were operationalized with set criteria for identification and with explained examples.

The Multiple Representations and Mathematical Reasoning a priori epistemological resources were adapted to better suit the purpose and data collected for this study. Specifically, Jones (2015) included equations as another representation form in the Multiple Representations but the purpose of this study was to tease apart participants' mathematics and physics epistemological resources. Therefore, the use of equations was not included in the Multiple Representations operationalizations. The Mathematical Reasoning epistemological resource was also adapted. In Jones' (2015) operationalization, participants discussing an equation, manipulating an equation, or discussing a graph were all included in the Mathematical Reasoning. In order to more finely describe the epistemological components of participants' Mathematical Reasoning, this code was broken down into three separate codes - namely Mathematica Reasoning—Equation, Mathematical Reasoning—Manipulation, and Mathematical Reasoning—Graph.

An example of a physics epistemological resource that emerged in this study is Calculation which was identified when a student discussed or conducted a calculation. This relates to a participant trusting the knowledge generated when following accurate mathematical formalisms. An instance where the calculation epistemological resource was identified is shown below:

Ana: Okay so torque two is equal to
Andrea: its fifty-five Newtons, okay. Point zero two fives times fifty
five. Okay so th-torque two is one point seven five
Ana: meters times fifty five Newtons times one
Andrea: seventeen
Ana: Oh it's awesome!
Andrea: Aren't we awesome. [sound of button pushing on calculator]
Ana: Point two fifty at fifty five Newtons did you get thirteen point
seventy five?

In the first line of this except, Ana initiates the calculation by saying the torque of interest is "equal to". Then Andrea picks up the calculation in the second line describing the numbers and how they are related in the equation. In the final line, Ana indicates the result of their calculation. In this instance, both participants performed a calculation and trusted that their use of accurate mathematical technique will lead to a trustable answer. This is only one of many epistemological resources that were identified in this study (see Appendix B for operationalizations and examples of each physics epistemological resource identified in this study).

Validity and Reliability. In order to investigate the reliability of both the emergent and a priori physics epistemological resource coding, a sample of 10% of the epistemological resource instances were coded by an additional rater. During the inter-rater reliability process, the second rater was trained in the operationalizations of the physics epistemological resources, coded a sample excerpt with the primary researcher, independently coded 10% of the data, and then discussed the findings with the primary researcher. After discussion, the primary researcher and secondary rater came to agreement on all physics epistemological resources included in this study.

Findings and Discussion

In this section, the findings of this study as well as a discussion of these findings will be presented. A full list of physics epistemological resources identified in the audio recordings is presented and discussed. This will be followed by a presentation and discussion of the usage patterns of these physics epistemological resources in order to address research question three. Finally, a discussion of the findings related to the third research question will be presented.

Epistemological Resources. Through the emergent and a priori coding, 837 total instances of 25 distinct physics epistemological resources were identified (see Appendix B for the operationalization and an example of each epistemological resource identified). Shown in Table 2 are the total number of instances that each physics epistemological resource was identified for each group of participants. These instances were then totaled across all groups. The last column states the number of problems out of 9 problems in total in which a particular physics epistemological resource was identified. One thing to note is the uneven number of participants included in each group.

Table 2

Physics Epistemological Resources Employed by Group

Physics Epistemological Resource		L/L	L/H	H/H	Total	Number Problems Present
Calculation		17	13	18	48	8
Causal Reasoning	†	0	2	2	4	4
Consistency	†	1	1	5	7	4
Contrasting Cases	†	15	5	10	30	7
Deductive Reasoning	†	5	1	9	15	5
Equation		43	38	36	116	8
Experimentation	†	0	3	0	3	1
If It's Given It Must Be Used		7	0	0	7	3
Inductive Reasoning	†	1	3	0	4	3
Invoking Authority		34	19	22	75	9
Knowledge as Fabricated Stuff		0	2	0	2	1
Knowledge from Direct Observation	†	2	3	5	10	5
Limitations of Model	†	5	2	1	8	3
Mathematical Reasoning—Equation		46	42	42	130	8
Mathematical Reasoning –Manipulation		30	28	19	77	8
Mathematical Reasoning—Graph		1	6	16	23	2
Meaning to Symbols		10	3	8	21	5
Mechanistic Reasoning	†	0	1	4	5	2
Multiple Representations	†	9	1	8	18	7
Peer Cognitive Awareness	†	75	57	53	185	9
Personal Cognitive Awareness	†	1	0	4	5	2
Physical Intuition		1	1	0	2	2
Plausibility	†	3	0	0	3	2
Relative Value of Knowledge	†	0	0	1	1	1
Sense Making	†	0	0	1	1	1
Total		318	248	271	837	9
Number of Problems		6	6	6	9	
Number of Participants		4	3	3	10	

Note. † indicates a priori physics epistemological resources from Jones, 2015. All other resources were emergently identified in this study.

As seen in Table 2, participants employed 25 distinct physics epistemological resources as they solved physics problems. This indicates that participants employ a range of resources as they solve differing problems.

Frequency of Epistemological Resource Usage. The frequency of usage of each of the physics epistemological resources was examined in order to investigate physics epistemological resource usage patterns. In Table 3, the total number of instances and number of problems in which each physics epistemological resource was identified as well as percent of total instances for each resource is displayed. The data has been aggregated across all participants. The physics epistemological resources are order from highest number of total instances to lowest number of total instances.

Table 3

Physics Epistemological Resource Usage Patterns

Physics Epistemological Resource		Total Instances	% of Total Instances	# Problems Present
Peer Cognitive Awareness	†	185	22.10	9
Mathematical Reasoning—Equation		130	15.53	8
Equation		116	13.86	8
Mathematical Reasoning—Manipulation		77	9.20	8
Invoking Authority		75	8.96	9
Calculation		48	5.73	8
Contrasting Cases	†	30	3.58	7
Mathematical Reasoning—Graph		23	2.75	2
Meaning to Symbols		21	2.51	5
Multiple Representations	†	18	2.15	7
Deductive Reasoning	†	15	1.79	5
Knowledge from Direct Observation	†	10	1.19	5
Limitations of Model	†	8	0.96	3
Consistency	†	7	0.84	4
Mechanistic Reasoning	†	5	0.60	2
Personal Cognitive Awareness	†	5	0.60	2
Causal Reasoning	†	4	0.48	4
Inductive Reasoning	†	4	0.48	3

Experimentation	†	3	0.36	1
Plausibility	†	3	0.36	2
Knowledge as Fabricated Stuff		2	0.24	1
Physical Intuition		2	0.24	2
Relative Value of Knowledge	†	1	0.12	1
Sense Making	†	1	0.12	1
Total		837	100	9

Note. † indicates a priori physics epistemological resources from Jones, 2015. All other resources were emergently identified in this study.

The second most commonly employed physics epistemological resource was Mathematical Reasoning—Equation resource constituting 130 instances out of the 837 total instances (15.53%). Mathematical Reasoning—Equation was identified when a participant discussed an equation, relationship between variables, and/or the form of a relationship. An example in context of this resource activation is shown below.

Ana: So momentum is…P final equation P initial right?

Ana is discussing the relationship between initial momentum and final momentum thereby invoking the Mathematical Reasoning—Equation epistemological resource. The high number of instances for this resource likely was affected by the types of problems that the participants were asked to solve as well as the course context details. The problems the participants were solved were chosen because they require students to use both mathematics and physics knowledge and skills to solve. Most of the problems selected required participants to solve for a symbolic solution which requires the use of mathematical expressions necessitating the use of mathematical reasoning. Also, the courses in which the data were collected are taught in a way that promotes the use of mathematical reasoning as a strategy to solve problems. The combination of these factors may have contributed to the high number of Mathematical Reasoning—Equation, Mathematical Reasoning—Manipulation, Mathematical reasoning—Graph epistemological resource instances. These are just two examples of the physics epistemological resources employed while participants solved physics problems. Another interesting aspect to these data is differences in physics epistemological resource usage across participants with differing backgrounds.

Inter-Group Differences. The literature base suggests differences in physics epistemological resource usage due to differences in participants' prior experiences in mathematics and physics (Hammer & Elby, 2000). In order to investigate if in fact these differences from the data in this, the physics epistemological resources were totaled for each group and compared to one another. Shown in Table 4 is the percent of total instances for each physics epistemological resource for each group (e.g., the Mathematical Reasoning—Equation epistemological resource was employed 46 out of the 318 total instances for the L/L, therefore it is shown as 14.47% in Table 4). Also shown is the percent of the total instances for all groups combined for each physics epistemological resource.

Table 4

Percent Physics Epistemological Resource Use for Each Group

Physics Epistemological Resource		L/L Group Percent	L/H Group Percent	H/H Group Percent	Percent Total
Calculation		5.35	5.24	6.64	5.73
Causal Reasoning	†	0.00	0.81	0.74	0.48
Consistency	†	0.31	0.40	1.85	0.84
Contrasting Cases	†	4.72	2.02	3.69	3.58
Deductive Reasoning	†	1.57	0.40	3.32	1.79
Equation		13.21	15.32	13.28	13.86
Experimentation	†	0.00	1.21	0.00	0.36

If It’s Given It Must Be Used		2.20	0.00	0.00	0.84
Inductive Reasoning	†	0.31	1.21	0.00	0.48
Invoking Authority		10.69	7.66	8.12	8.96
Knowledge as Fabricated Stuff		0.00	0.81	0.00	0.24

Table 3 Continued

Knowledge from Direct Observation	†	0.63	1.21	1.85	1.19
Limitations of Model	†	1.57	0.81	0.37	0.96
Mathematical Reasoning—Equation		14.47	16.94	15.50	15.53
Mathematical Reasoning—Manipulation		9.43	11.29	7.01	9.20
Mathematical Reasoning—Graph		0.31	2.42	5.90	2.75
Meaning to Symbols	†	3.14	1.21	2.95	2.51
Mechanistic Reasoning	†	0.00	0.40	1.48	0.60
Multiple Representations	†	2.83	0.40	2.95	2.15
Peer Cognitive Awareness	†	23.58	22.98	19.56	22.10
Personal Cognitive Awareness	†	0.31	0.00	1.48	0.60
Physical Intuition		0.31	0.40	0.00	0.24
Plausibility	†	0.94	0.00	0.00	0.36
Relative Value of Knowledge	†	0.00	0.00	0.37	0.12
Sense Making	†	0.00	0.00	0.37	0.12
Total		100%	100%	100%	100%

Note. † indicates a priori physics epistemological resources from Jones, 2015. All other resources were emergently identified in this study.

Combining the data from Table 2 and Table 4, the following resources were applied similar amounts of times in each of the three groups: Calculation, Consistency, Contrasting Cases, Equation, Inductive Reasoning, Knowledge from Direct Observation, Limitations of Model, Mathematical Reasoning—Equation, Mathematical Reasoning—Manipulation, Meaning to Symbols, Mechanistic Reasoning, Peer Cognitive Awareness, and Physical Intuition.

There were six resources that were only used by one group; namely Experimentation was only used by the L/H group, If It’s Given It Must Be Used was only used by the L/L group, Knowledge as Fabricated Stuff was only used by the L/H group (and even more precisely was only used by Ana from the L/H group), Plausibility was only used by the L/L group, and Relative Value of Knowledge and Sense Making were only used by the H/H group. This implies that physics epistemological resource usage varied amongst students with different academic backgrounds, which is consistent with the tenants of the epistemological resources framework.

Another interesting example is the Causal Reasoning epistemological which was employed twice by the L/H and H/H groups but never by the L/L group. Also, the Deductive Reasoning resource was employed more often by the H/H group than the L/L and L/H groups. On the other end of the spectrum, the Invoking Authority was employed appreciably more often by the L/L group than either the L/H or H/H group. Similarly, the Mathematical Reasoning—Graph resource was employed significantly more frequently by the H/H than either the L/L or L/H groups. These results indicate that students with more prior experience with science and mathematics will employ resources similar to experts (Causal Reasoning and Deductive Reasoning were a priori codes from a study of physics experts; Jones, 2015). On the other hand, students with less prior experience in mathematics and science use less physics epistemological resources in common with physics experts. This difference is likely due to the content of the questions the H/H participants solved (for details about the content of the questions the participants solved, see Appendix A).

A surprising finding is that the Multiple Representations was used significantly less by the L/H group than either the L/L or H/H groups. This result is interesting because the literature base indicates that epistemological resource usage patterns should be different based on students' previous experience and that students will more experience in the discipline should have more expert-like usages of their epistemological resources. Therefore, one would expect that a higher order resource like Multiple Representations would be used most commonly by the H/H group and least commonly by the L/L group with the L/H group somewhere in the middle. The findings from this study do not follow this pattern of epistemological resource usage. This contrasts with the extant literature about epistemological resource usage. Although another interpretation could be that grouping data based on the participants' number of previously completed mathematics and science classes does not aptly capture their prior experience. This interpretation aligns with current epistemological resources research and would add a study supporting the connection between prior experience and epistemological resource usage.

These differences between groups of participants could be due to a myriad of reasons, such as different resource usages based on content of problem or group dynamics, whose investigation was beyond the scope of this study. Future research should be conducted to tease apart the possible sources of group differences.

Delimitations

The delimitations for this study fall into two separate categories, namely the format of the study and the context in which the data were collected. The first delimitation comes from the purpose and associated research questions for this study. The purpose of the study was to identify and characterize introductory physics students' physics epistemological resources and their associated usage patterns. This study was intended give a macroscopic view of the resources used by introductory physics students while they solve many different types of physics problems. This leaves many of the details of the source of the differences between physics epistemological resources usage ambiguous.

A second delimitation involves the setting in which the data were collected. The data were collected in two introductory physics courses that were taught by the primary researcher of this study. Due to the primary researcher's understanding of the epistemological resources framework, some of the epistemological ideas were discussed in class and the framework shaped how these courses were taught and administered. During the laboratory sections of the course where the data were collected, the instructor encouraged and actively promoted students asking the instructor questions. Therefore, this could have led to an increase in the number of instances Invoking Authority epistemological resources due to the course structure instead of due to some inherent difference in the participants' "natural" epistemological resource usage.

Limitations

A limitation for this study is the specific participants that participated in the study. The participants of this study were drawn from the population of students enrolled in the physics courses during the summer semester. The summer semesters typically have a smaller enrollment; and therefore, afforded only a small sample size for this study. Also, the participants were not particularly diverse. For example, none of the participants has a lower number of previously completed science classes and a higher number of previously completed mathematics classes.

Another limiting factor in the data analysis was the lower number of instances of some of the physics epistemological resources (e.g. Causal Reasoning, Consistency, Experimentation, If It's Given It Must Be Used, Inductive Reasoning, Knowledge as Fabricated Stuff, Knowledge from Direct Observation, Limitations of Model, Mechanistic Reasoning, Personal Cognitive Awareness, Physical Intuition, Plausibility, Relative Value of Knowledge, and Sense Making). This made comparisons and generalizations difficult solely due to the low number of instances. In future research, these limitations should be addressed.

Conclusions and Implications

Introductory physics students’ physics epistemological resources were identified emergently and using an a priori coding scheme from Jones’ study (2015). A total of 25 physics epistemological resources were identified through rigorous coding an recording of transcripts of students’ group think-alouds while solving physics problems in a laboratory setting. The 5 most commonly used resources were Peer Cognitive Awareness, Mathematical Reasoning—Equation, Equation, Mathematical Reasoning—Manipulation, and Invoking Authority which in total accounted for 586 of the 837 instances identified (69.7% of total instances).

The data revealed that there were appreciable differences in physics epistemological resource usage between participants with different mathematics and physics backgrounds. Specifically, the physics epistemological resources were identified were not uniformly invoked across students of varying background. Students with more experience with science and mathematics (as measured by their previously completed mathematics and physics problems) employed more resources that physics experts also employed. Conversely, the physics epistemological resource usages of students with less science and mathematics experience were not similar with physics experts.

The differences in participants’ physics epistemological resource usage implies that increasing students’ experience in mathematics and science can help to broaden their physics epistemological resource usages. Therefore, classroom teachers should be aware that their students may have physics epistemological resource activation patterns that can hinder their success in introductory physics. And they should help to promote students' epistemological development in their courses along with teaching the content of the course.

This study adds to the literature in that it is the only study to investigate the epistemological resource usage of introductory physics students. The epistemological resources identified in this study will be a baseline for future studies.

The differences in physics epistemological resource usage were solely identified in this study. The differences between participants' epistemological resource usage could be due to the nature of the physics content of the problem, the nature of the mathematics content of the problem, the different difficulties and types of the problems, the timing during the semester in which the problem was solved, the group dynamics between the participants in groups, the differences in prior experience both in mathematics and physics as measured more finely than by previous number of courses completed, the differences in motivation level from day to day, and numbers other possible reasons. Future should be conducted in order to sort out this ambiguity and more precisely determine the reasons for the differences within and among students.

IV. STUDY II: EPISTEMOLOGICAL RESOURCE USAGE VARIATIONS

Introduction

The Physics Education Research (PER) community recently began investigating the personal epistemology of physics students, faculty, and professionals. Because physics and mathematics are intrinsically intertwined, if students are to be successful in introductory physics courses they must be able to use their mathematics knowledge and skills simultaneously (Pereira de Ataíde & Greca, 2013). But if the students conceive of knowledge in these two disciplines differently, it can cause difficulties in using mathematics knowledge in a physics context. Therefore, the purpose of this dissertation is to investigate the epistemological underpinnings of student difficulties in introductory physics.

Numerous studies have shown that students' personal epistemologies have a profound impact on multiple aspects of their learning, including conceptual learning gains, (May & Etkina, 2002), grade point average (Schommer, 1993), problem-solving skills (Hammer, 1994), course retention (Perkins et al., 2004), and interest in science (Richards, Conlin, Gupta, & Elby, 2012). Many of these studies are underpinned by the Epistemological Beliefs theoretical framework (Schommer, 1990). In this framework, epistemology is described as independent large-grained beliefs that are relatively stable over time. These beliefs can be measured using Likert-style scales such as the Epistemological Beliefs About Physical Science survey (EBAPS; White et al., 1999) or the Colorado Learning Attitudes about Science Survey (CLASS; Adams et al., 2005). Other studies have found components of epistemology that are domain-general (invariant across disciplines) and other components that are domain-specific (vary across disciplines) but few have compared epistemologies of similar disciplines (Muis et al., 2006). While these surveys allow for the collection of large data sets about student epistemology, the large-grained nature of Epistemological Beliefs do not allow for comparisons of epistemologies of related disciplines (e.g., mathematics and physics). Therefore, this study was framed with a finer-grained theory in order to investigate the epistemologies about mathematics and physics of students enrolled in introductory physics courses using the Epistemological Resources framework.

The Epistemological Resources theoretical framework describes personal epistemology as composed of fine-grained pieces of cognitive structure that color how students view the world around them. Bing and Redish (2009) state:

> An epistemological resource is a cognitive modeling element. It represents a tightly bundled packet of information that, when activated by the mind, leads the individual to interpret the knowledge at hand in a certain light. But an epistemological resource is a control structure, not a concept; epistemological resources affect how students perceive the nature of the situation under current consideration and they control what conceptual resources are brought to bear. (p. 020108-3)

Hammer and Elby (2000) state that students subconsciously draw upon these resources as they identify features of the problems they are solving they deem to be salient. These activation and associated inhibition patterns of resources are shaped by their prior experiences. For example, imagine that a student identifies a particular salient feature and employs resource X, which leads to a successful outcome. In the future, this student will be more likely to employ resource X when faced with the same salient features. Due to the fine-grained and subconscious nature of epistemological resources, students cannot readily articulate which resources they are invoking at any given time (Hammer & Elby, 2000). Therefore, students' words and actions must be observed in order to determine what resources are being employed. As opposed to Epistemological Beliefs, which are characterized on a novice to expert spectrum, Epistemological Resources are not intrinsically judged to be expert-like or novice-like but instead each instance of resource activation is determine to be appropriate or less appropriate usage based on context.

Although an all-inclusive list of epistemological resources does not exist in the extant literature, a few have been defined in the literature (Hammer & Elby, 2001; Bing & Redish, 2009; Jones, 2015). Unfortunately, most of these resources are only discussed in a single article. For example, the Invoking Authority epistemological resource describes trusting the knowledge procured from a perceived authority source such as a teacher, a textbook, or the internet (Bing & Redish, 2009).

This study is part of a larger investigation of the epistemological resources employed by introductory physics students while solving mathematics and physics problems. The research questions guiding this inquiry were:

1) Which epistemological resources do introductory physics students employ as they solve physics and mathematics problems?

2) What are their physics and mathematics epistemological resource usage patterns while solving physics and mathematics problems?

Methodology

The purpose of this phenomenological study was to investigate the physics and mathematics epistemological resource usage of students that are enrolled in introductory physics courses. Video data were collected during office-hour sessions while participants discussed their thinking as they solved physics and mathematics problems. The recordings were transcribed verbatim and these transcriptions were the main data source for the study. In order to determine the physics and mathematics epistemological resources employed by participants, content analysis for both latent and manifest codes was conducted (Neuendorf, 2002; Downe-Wamboldt, 1992). The epistemological resources were using two a priori epistemological resource operationalizations, namely internal and external. The internal operationalizations were defined during a pilot study on a similar population of participants (Scanlon, 2016). The external operationalizations were from a study conducted by Jones (2015) on the epistemological resources employed by physics experts as they solved novel physics problems.

Participants. The data for this study were collected at a small, private liberal arts university in Texas. The participants in this study were enrolled in the first introductory physics course in the algebra-based physics sequence. This Introductory Physics for the Life Science (IPLS) course was developed to highlight the applicability of physics topics to the future careers of the students in this class; namely biology, chemistry, kinesiology, and pre-health professions majors.

Shown in Table 5 is the demographic and academic background (measured by number of previously completed mathematics and science classes) data for the four selected participants.

Table 5

Participant Demographic and Background Academic Information

Name	Gender	Years in College	Number Science Courses	Number Math Courses	Use of Signs
Brooke	Female	3.5	12	3	Consistent
Jaime	Male	1.5	6	1	Inconsistent
Julia	Female	3.5	17	3	Consistent
Marie	Male	3.0	14	4	Inconsistent

Measures and Data Collection. In order to determine the epistemological resources employed, the participants solved mathematics and physics problems and were observed while doing so. The problem-solving sessions occurred during the office-hours of the primary researcher, who was also the instructor of record for the course, to give an authentic problem-solving context. This was necessary due to the highly context-dependent nature of epistemological resource activation. An interactive, semi-structured observation protocol was implemented while participants were solving the problems (see Appendix C for the interactive observation protocol). In each of the three sessions, participants solved one mathematics and one physics problem. All sessions were video recorded during one semester of an introductory, algebra-based physics course designed for life science students.

The physics problems the participants solved were course-assigned homework problems from their physics course on the topics of graphical kinematics, equilibrium and forces, and energy conservation. The mathematics problems were versions of the physics problems where the background information had been removed. For example, if the physics problem required students to solve a system of two linear equations with two variables and three constants, then the mathematics problem required participants to solve a similar system of equations with variables x and y and constants A, B, and C. The physics and mathematics problems were counterbalanced (Gersten et al., 2005), meaning that half of the participants solved the mathematics problem first and the physics problem second and vice versa. Then the order was switched for each subsequent problem solving sessions.

Data Analysis. Participants' epistemological resource usage can be determined from their words and actions because they do not have articulable access to the resources due to their fine-grained nature (Hammer & Elby, 2000). The main data set for this study was the transcripts of the office-hour problem-solving sessions. Content analysis for both latent and manifest codes were conducted on the transcripts and video recordings of the participants' words and actions (Neuendorf, 2002; Downe-Wamboldt, 1992).

An a priori coding scheme from both internal and external sources was employed in order to identify the epistemological resources employed by participants. The external operationalizations of epistemological resources were from Jones' (2015) study of the physics epistemological resources employed by experts as they solve novel physics problems. The internal operationalizations of epistemological resources came from a pilot study of the physics epistemological resources employed by introductory physics students while solving physics problems in groups (Scanlon, 2016).

After the instances of physics and mathematics epistemological resource usage were identified, similarities and differences in the physics and mathematics epistemological resource usage patterns between participants were investigated.

Traditional statistical comparisons (e.g., t-tests) were not appropriate due to the small sample size. Therefore, as a method for descriptive comparison the Bray-Curtis dissimilarity metric was used (Greenacre & Primicerio, 2013). The Bray-Curtis metric (b) is calculated by:

$$b = \frac{|n_i - n_j|}{n_i + n_j}$$

where n_i is the number of instances that a particular resource was employed by the ith participant and n_j is the number of instances that a particular resource was employed by the jth participant (Greenacre & Primicerio, 2013). Because this is the first study comparing epistemological resource usage between disciplines, there is not a standard way of comparing the differences. Therefore, the Bray-Curtis dissimilarity was operationally defined for this study as a measure of meaningful difference between participants' usage of epistemological resources. It is the difference in the number of instances a particular resource was employed between two participants divided by the sum of the number of instances a particular resources was employed by both participants.

Validity and Reliability. In order to investigate the reliability of the epistemological resource coding, an inter-rater reliability process was conducted between the primary researcher and two secondary raters. In this process, the secondary raters independently coded approximately 12% of the total instances after being trained on the epistemological resource operationalizations. The instances of physics and mathematics epistemological resources coded by the raters were systematically selected to be from a range of participants, problem-solving sessions, internal and external a priori codes, types of problems, and to span inference level associated with the epistemological resource instance (see Appendix F for more information about the inter-rater reliability process). During the inter-rater reliability process, the primary researcher and the secondary raters coded an instance of an epistemological resource together. Then the secondary raters independently coded the pre-selected instances for that same epistemological resource. If there was disagreement was independent coding, the raters and primary research discussed until agreement was reached. This process was completed iteratively for each epistemological resource identified in this study. All of the epistemological resources included in this study were agreed upon by the primary researcher and both secondary raters.

Sampling. The introductory physics course in which the participants were enrolled was the basis for the initial purposive sampling. Specifically, the purpose of this study was to investigate the epistemological resource usage of students enrolled in introductory, algebra-based physics courses. Next, the students that opted into the study were included in the study and this constituted convenience sampling. A total of 16 participants completed all three problem-solving sessions.

After data collection, the data were sampled based on the participants' background academic variables (including incoming attitudes and beliefs, incoming conceptual understanding, number of previously completed mathematics and science classes). After this criterion sampling, a total of 12 participants' data were transcribed verbatim to include the words, pauses, and actions of the participants through which over 2,000 instances of physics and mathematics epistemological resource usage were identified.

Rather than presenting all of the instances of epistemological resource usage, an example will be analyzed and discussed. The ways in which students used signs in energy conservation problems was chosen to provide a meaningful example. The use of signs was chosen as an example because it highlighted the idea that students' mathematics knowledge and skills are not the reason students struggle with mathematics in a physics context but instead also relates to their epistemologies about physics and mathematics Two participants showed an inconsistent use of signs between physics and mathematics interpretations while solving the energy physics problem. Shown in the transcript below is Jaime's inconsistent use of signs:

Jaime: Which means that she starts off initially with some, gravity -or um, potential gravitational energy. So I'm gonna say U of P and then she ends with kinetic energy. So, U of P minus kinetic energy is also equal to the change in energy because that's changing as she goes down.

Interviewer: Okay. So why do you do UP minus KE? [emphasis on 'minus']

Jaime: Um just because -it's initial -oh I guess it be the other way around–oh I mean -I don't think it really matters as long as one is minus because you're gonna want to set those equal to each other.

In this excerpt, Jaime was correct with his mathematics use of signs (e.g., $x - y = 0$ is the same as $y - x = 0$) but incorrect with this physics use of signs (e.g. $E_f - E_i = 0$ versus $E_i - E_f = 0$). Therefore this was identified as an inconsistent use of signs. Marie had a similar inconsistency in her use of signs as shown in the transcript below.

Marie: Okay. So that means um [short pause] that Delta E equals zero and is equal to the gravitational potential energy minus the kinetic energy.

Interviewer: So how did you get from Delta E to GPE minus KE?

Marie: Oh I should write it the other way around, because final minus initial. Though I really don't -I don't think it really matters right?

In this excerpt, Marie also was correct in her mathematical usage of sign ($GPE - KE = 0$ is mathematically the same as $KE - GPE = 0$) while her physics was identical to Jaime’s. Therefore, Marie’s sign usage was inconsistent.

In order to compare, two participants with consistent use of signs while solving an energy conservation problem were selected; namely Brooke and Julia. Shown below is an excerpt from Julia’s discussion while solving the energy conservation problem.

Julia: [Agreeing] So the f-final e-energy would be my kinetic energy and then my initial would be the gravitational potential. So UGI and then plus kinetic I and this is final plus UG final. And then we know that UG final is zero so that's why I kind of like didn't include it at the beginning but I realized that I have to include it symbolically.
Interviewer: [nods head] Okay.
Julia: Um and then the kinetic initial was zero because she's at rest.
Interviewer: Okay.
Julia: Um so that leaves us with KF
Interviewer: What does this equal?
Julia: Oh this equal to zero.
Interviewer: [Agreeing]
Julia: And that’s –ah K F minus UGI is equal to zero.

In this excerpt, Julia ascribes the correct type of energy to be initial and to be final such that during the change in energy calculation the physics and mathematics sign interpretations are consistent. Finally, in the excerpt below is part of Brooke’s discussion of the energy conservation problem.

Brooke: Okay. So then Change in Mechanical Energy equals Change in Kinetic plus change in Gravitational Potential plus Change in Spring Potential.
Interviewer: Okay.

Brooke: And so all of that equals zero. So then this could be rewritten as Kinetic Final plus Gravity Potential final plus Spring Potential Final equals Kinetic Initial plus Spring Gravitational Initial plus.

Similar to Julia, Brooke’s use of signs was consistent between the mathematics and physics interpretations. In addition to showing an inconstancy (or consistency) in mathematics and physics sign usage, these examples provide a rich set of data relating to participants’ epistemological resources. Therefore, the rest of this manuscript will focus on the epistemological resources employed by Brooke, Jaime, Julia, and Marie while solving three mathematics and three physics problems.

Findings and Discussion

Epistemological Resources. During the data analysis, a total of 17 distinct epistemological resources were identified in the three problem-solving session of the four selected participants. Shown in Table 6 is the total number of instances that each participant employed the top 10 most commonly applied resources for these participants.

The Contrasting Cases resource was identified when a participant compared two or more cases (i.e., particular set of circumstances) to each other (Jones, 2015). The Inductive Reasoning resource describes a type of reasoning where a participant starts with a premise from observations and derives a conclusion from the premise (Jones, 2015). The Invoking authority resource was identified when a participant directly invoked a definition, equation, or concept from an authority source such as a teacher, textbook, or trusted peer (Scanlon, 2016).

Table 6

Total Instances Epistemological Resources Usage

		Consistent Sign Usage		Inconsistent Sign Usage		
Epistemological Resources		Brooke	Julia	Jaime	Marie	Total
Contrasting Cases	*	4	2	0	0	6
Inductive Reasoning	*	10	0	4	2	16
Invoking Authority		5	7	0	3	15
Mathematical Reasoning-Equation		54	60	83	56	253
Mathematical Reasoning-Graph		28	32	45	22	127
Mathematical Reasoning-Manipulation		34	39	52	27	152
Meaning to Symbols		4	8	10	8	30
Multiple Representations	*	6	4	6	5	21
Personal Cognitive Awareness	*	4	8	12	7	31
Physical Intuition		7	12	15	8	42
Total		156	172	227	138	693

Note. The * indicates the resource came from the external operationalization (Jones, 2015).

The Meaning to Symbols resource was identified when a participant transcribed the problem into variables or ascribed meaning to symbols given in the problem (Scanlon, 2016). The Multiple Representations epistemological resource was identified when the participant invokes a non-verbal, non-equation representation of the situation such as a diagram (Jones, 2015). The Personal Cognitive Awareness resource relates to the participant's metacognition and can be identified when a participant references what (s)he is thinking (Jones, 2015). The Physical Intuition resource relates to participants' conceptions of the how the world works based on their experiences and was identified when they discussed knowing something due to their prior experiences in the world (Jones, 2015).

The Mathematical Reasoning—Equation epistemological resource is an aspect of mathematical reasoning related to discussing, describing the relationship and/or form of relationship between variables. The Mathematical Reasoning—Graph epistemological is resource related to discussing, interpreting or making a graph component of mathematical reasoning. Finally, the Mathematical Reasoning—Manipulation resource describes the mathematical reasoning related to manipulating an equation or conducting a calculation (Jones, 2015; Scanlon, 2016).

The most commonly employed epistemological resources were the three Mathematical Reasoning resources which in combination accounted for nearly 77% of the 693 total instances of resource usage identified. The next most commonly employed resources was the Physical Intuition resource which was employed for a total of 42 out the 693 instances (6%). All four participants solved three mathematics and three physics problems but the time for each to complete the problems varied which could contribute to the differences in total number of epistemological resources instances amongst the participants. Or the inconsistent sign usage participants could have trouble with the concepts which led them to try our more resources (e.g., like Jaime) or finish faster without employing as many resources (e.g., like Marie).

Intra-Group Comparison. In order to investigate the similarities and differences in epistemological resource usage between the consistent and inconsistent sign usage groups, the Bray-Curtis dissimilarity metric was calculated. This metric compared the raw number of instances in which a particular resource was identified between two participants and was operationally defined as a meaningful way to describe differences. Shown in Table 7 is the Bray-Curtis dissimilarity multiplied by one hundred to compare intra-group resource usage. If the raw difference in number of instances equaled one, this difference was operationally defined as not meaningful. For example, for the mathematics epistemological resources comparison of Jaime and Marie, Marie employed

Invoking Authority once while Jaime did not employ this resource. This lead to a Bray-Curtis dissimilarity metric value of 100 but this difference was not defined as meaningful due to the raw difference in number of instances equaling one. The cells with a † show the meaningful dissimilarities using the Bray-Curtis dissimilarity approach, which were defined as greater than the mean dissimilarity across all participants, specifically 32.

Table 7

Intra-Group Resource Usage Comparison Bray-Curtis Dissimilarities

	Consistent Sign Usage		Inconsistent Sign Usage	
	Physics	Math	Physics	Math
Epistemological Resources	Brooke and Julia	Brooke and Julia	Jaime and Marie	Jaime and Marie
Contrasting Cases	20.0	100	0	0
Inductive Reasoning	100 †	0	33.3	0
Invoking Authority	55.6 †	100 †	100 †	100
MR—Equation	5.4	4.8	14.9	31.6
MR—Graph	12.0	2.9	42.1 †	24.1
MR—Manipulation	12.2	0	30.4	33.3 †
Meaning to Symbols	27.3	100	12.5	0
Multiple Representations	20.0	0	9.1	0
Personal Cognitive Awareness	42.9 †	20.0	20.0	50.0 †
Physical Intuition	26.3	0	30.4	0

Note. † indicates meaningful Bray-Curtis dissimilarity values defined as greater than 32.

As shown in Table 7, the participants within the same group do not have many differences in resource usage. The largest raw difference was with the Mathematical Reasoning—Graph epistemological resource between Jaime and Marie while solving physics problems and the raw difference was 11 instances. This implies that participants within groups employed physics and mathematics similarly. Overall, the participants' use of signs while solving a conservation of energy problem allowed for the formation of groups in which participants similarly employed epistemological resources while solving both mathematics and physics problems.

Inter-Group Comparison. Participants' data were placed into two groups based on the consistency or inconsistency of their sign usage during an energy conservation problem. The epistemological resources of these two groups were compared using the Bray-Curtis dissimilarity metric. Shown in Table 8 are the findings for the comparison between each consistent sign usage group member and each inconsistent sign usage group members' physics epistemological resource usage (includes data from all three problem-solving sessions).The cells with a † show meaningful Bray-Curtis dissimilarity values.

Table 8

Inter-Group Physics Resource Usage Comparison Bray-Curtis Dissimilarities

Epistemological Resource	Physics			
	Brooke and Jaime	Brooke and Marie	Julia and Jaime	Julia and Marie
Contrasting Cases	100 †	100 †	100 †	100 †
Inductive Reasoning	42.9 †	66.7 †	100 †	100 †
Invoking Authority	100 †	0.00	100 †	55.6†
Mathematical Reasoning—Equation	13.7	1.10	8.40	6.50
Mathematical Reasoning—Graph	42.1 †	0.00	31.7 †	12.0
Mathematical Reasoning—Manipulation	25.0	5.90	13.2	17.9
Meaning to Symbols	38.5 †	27.3	12.5	0.00
Multiple Representations	0.00	9.10	20.0	11.1
Personal Cognitive Awareness	63.6 †	50.0 †	28.6	9.10
Physical Intuition	36.4 †	6.70	11.1	20.0

Note. † indicates meaningful Bray-Curtis dissimilarity values defined as greater than 32.
[a] Consistent sign users are listed first and inconsistent sign usage are listed second.

As indicated by the large number of meaningful dissimilarities between participants' epistemological resources in Table 8, the physics epistemological resource usage while solving physics problems is meaningfully different between groups. The Contrasting Cases and Inductive Reasoning resources were differently employed inter-group while Mathematical Reasoning—Equation and Multiple Representations were similarly applied during physics problem-solving.

Shown in Table 9 are the findings for the comparison between each consistent sign usage group member and each inconsistent sign usage group members' mathematics epistemological resource usage (includes data from all three problem-solving sessions). The cells with a † show meaningful Bray-Curtis dissimilarity values.

Table 9

Inter-Group Mathematics Resource Usage Comparison Bray-Curtis Dissimilarities

	Mathematics			
Epistemological Resources	Brooke and Jaime	Brooke and Marie	Julia and Jaime	Julia and Marie
Contrasting Cases	100	100	0.00	0.00
Inductive Reasoning	0.00	0.00	0.00	0.00
Invoking Authority	100 †	50.0 †	0.00	100
Mathematical Reasoning—Equation	42.9	13.0	38.9†	8.30
Mathematical Reasoning—Graph	2.90	21.4	0.00	24.1
Mathematical Reasoning—Manipulation	15.8	18.5	15.8	18.5
Meaning to Symbols	100	100	0.00	0.00
Multiple Representation	0.00	0.00	0.00	0.00
Personal Cognitive Awareness	20.0	33.3 †	0.00	50.0†
Physical Intuition	0.00	0.00	0.00	0.00

Note. † indicates meaningful Bray-Curtis dissimilarity values defined as greater than 32.
^{a} Consistent sign users are listed first and inconsistent sign usage are listed second.

In contrast, the mathematics epistemological resources participants employed while solving mathematics problems showed appreciably fewer differences as seen in Table 9. For the mathematics problems, only five meaningful differences in mathematics epistemological resource application were identified inter-group. The epistemological resource usage between the two groups differed while solving physics problems and was similar while solving mathematics problems. Also, the participants who exhibited a consistent use of signs tended to use Contrasting Cases and Invoking Authority more than the participants who exhibited an inconsistent use of signs. This indicates the context-dependent nature of epistemological resource activation. These findings suggest that students’ consistency of sign usage may be epistemological in nature due to the differences in resources application while solving physics problems between the two groups.

Conclusions and Implications

Participant data were grouped into an inconsistent and consistent sign usage groups based on their discussion while solving an energy conservation problem. Appreciable differences in resource usage intra-group were not found. Also, differences in the resources applied while solving mathematics problems were not found between groups. In contrast, appreciable differences in resource usages were found between groups for the physics problem-solving sessions.

This implies that students’ inconsistent use of signs may be an epistemological issue—the physics epistemological resources employed by students with a consistent use of signs are meaningfully different than the physics resources employed by students with an inconsistent use of signs. The case of signs highlighted the differences in physics epistemological resource usage for groups of participants. A future targeted intervention should be developed in order to address the epistemological differences between students. Future work will focus on comparing epistemological resource usage differences by content of physics problems, by student demographic and prior academic variables, and by timing in semester.

V. STUDY III: EPISTEMOLOGICAL RESOURCES IN THE PHYSICS CLASSROOM

Introduction

Physics and mathematics are intrinsically intertwined (Arnol’d, 1999). Therefore, in order for students to be successful in a physics course, they must be able to use mathematics and physics knowledge and skills simultaneously. Previous research has argued that students may be unsuccessful in introductory physics courses because they lack the mathematics knowledge and skills necessary in order to understand physics (Hudson & McIntire, 1977; Hudson & Liberman, 1982; Meltzer, 2002; Tuminaro & Redish, 2003; Buick, 2007; Hubisz, 2009; Chediak, 2010). However, even the most mathematically prepared students still have difficulties in introductory physics courses. Tuminaro and Redish (2005) hypothesize these difficulties may be related to how students use their mathematics knowledge in a physics context. Due to the very different classroom environments in which students typically learn mathematics and science, they may think about knowledge differently in these two disciplines—that is, they may have different epistemologies about physics and mathematics. The purpose of this research is to explore one aspect of students’ difficulties with mathematics in a physics classroom that may not be due to a lack of knowledge and skills, but may instead be related to their epistemologies about mathematics and physics.

Epistemology

Epistemology is broadly defined as the nature, source, and justification of knowledge. Epistemology addresses questions such as where does knowledge come from, how quickly can knowledge be acquired, what counts as evidence, and how certain is knowledge (Hofer & Pintrich, 1997). Numerous studies have found that students' epistemologies affect the way they learn in a physics course including their conceptual learning gains (May & Etkina, 2002), grade point average (Schommer, 1993), problem-solving methods and skills (Hammer, 1994), physics course retention (Perkins et al., 2004), interest in science (Richards et al., 2012), and their learning of physics (Lising & Elby, 2004).

One epistemology theoretical framework from the Physics Education Research (PER) community is Epistemological Resources which are described as fine-grained pieces of cognitive structure that students subconsciously draw on and that color their view of a problem (Hammer & Elby, 2000). Epistemological Resource activation and inhibition patterns are based on students' prior experience; for example, if a student identifies a particular salient feature and employs resource A, which leads to a successful outcome, then when they identify the same salient feature in the future they are more likely to apply resource A (Hammer & Elby, 2002). Students draw from their wide array of epistemological resources while solving problems.

Because students' epistemologies affect multiple aspects of their interaction in a physics course, could their epistemology about physics and their epistemology about mathematics affect their use of mathematics in a physics context? To investigate this question, twelve introductory algebra-based physics students were observed while solving both mathematics and physics problems. The physics problems covered graphical kinematics, equilibrium and forces, and energy conservation topics. The mathematics problems were varied versions of the physics problems where the background information had been removed (see Appendix D for the physics and mathematics problem statements). For example, if physics problems required the use of mathematics to solve a quadratic expression with a trigonometric function, one variable, and four constants, then the mathematics problem required the same skills but with x as a variable and A, B, C, and D as constants. Students were observed during one-on-one office-hour sessions (see Appendix C for the Interactive Observation Protocol). The transcripts of the problem-solving sessions were then analyzed to determine the epistemological resources employed by students while solving mathematics problems and physics problems separately.

Epistemologies about Physics and Mathematics

The number of instances each epistemological resource was identified was tallied for the physics problem-solving and the mathematics problem-solving data. Meaningful differences were found in the number of instances epistemological resources were employed while participants solved mathematics problems versus when they solved physics problems. For example, the Inductive Reasoning resource, which describes a type of reasoning where a participant starts with a premise from observations and derives a conclusion from the premise, was only identified while participants solved physics problems. Specifically, it was identified 42 times while students were solving physics problems. Similarly, other reasoning epistemological resources (e.g., Analogical Reasoning, Causal Reasoning, Deductive Reasoning, and Mechanistic Reasoning; for a full listing of the epistemological resources identified including operationalizations and examples, see Appendix E) were only identified while students were solving physics problems. This difference is striking: none of the epistemological resources related to reasoning were employed while students solved mathematics problems. This may imply that students are implementing a memorized set of rules while solving mathematics problems instead of reasoning through their problem-solving.

The largest difference in raw number of instances of resources identified was for the Mathematical Reasoning—Equation epistemological resource, which is identified when a participant discussed the form of a relationship or invoked an equation (Scanlon, 2016). The Mathematical Reasoning—Equation resource was employed 539 times by participants as they solved physics problems and 183 times as they solved mathematics problems. This was also the most commonly employed resource for physics problem-solving. Frequently while participants solved physics problems they discussed the form of a relationship or invoked a physical relationship. In contrast, when participants solved mathematics problems they frequently simply restated the mathematical equation given as they were manipulating it. For example, in the excerpt below a student was solving a forces problem:

Student: And it's like the sum of forces
Instructor: [agreeing] [nods head]
Student: Is it MA—equals mass times acceleration.

In this excerpt, the student cites Newton's second law, thereby invoking the Mathematical Reasoning—Equation epistemological resource. The student then uses this relationship to motivate finding the sum of the forces acting on the object. In constrast, the same student in the excerpt below was solving problem involving a system of linear equations:

Student: Yeah. So the first equation AY minus BC equals zero. I'm going to solve that for Y

Instructor: Okay.
Student: equals everything else. Um so AY equals BC.

In this excerpt, the student is stating and restating the equation given in the problem thereby invoking the Mathematical Reasoning—Equation epistemological resource. Therefore, even though this resource was identified while the student solved both mathematics and physics problems, the epistemological resource was employed in largely differing situations again highlighting a difference in students' epistemologies about physics and mathematics.

Physical Intuition, where students draw upon their understanding of how the world works because of their experiences in the real world, was also differently employed for physics and mathematics problem-solving. Participants only invoked Physical Intuition twice while solving mathematics problems whereas they did so 119 times while solving physics problems. This is important because it shows that students do not attempt to check that their answer makes sense in the real world as they solve mathematics problems but they do while solving physics problems.

Similarly, the Multiple Representations epistemological resource, which was identified when participants employed a non-verbal, non-equation representation such as a diagram or a graph, was also differently applied across mathematics and physics problems. This resource was identified 43 times during physics problem-solving and only 3 times during mathematics problem-solving. This is important because it indicates that students do not attempt to use alternate mathematical representations while solving mathematics problems. They do not seek the best route to solving a problem—instead they plunge ahead with whatever representation first comes to mind. These examples are only a few of the meaningful differences in students' epistemological resource usage while solving mathematics and physics problems.

Overall, students employed epistemological resources differently while solving mathematics problems than they did while solving physics problems. This implies that students' epistemology about mathematics and epistemology about physics are likely different. This difference in epistemologies about physics and mathematics could contribute to students' difficulties in using mathematics in a physics context and to being successful in introductory physics courses.

Implications for Classroom Practice

Contrary to previous research (e.g., Buick, 2007), this study demonstrates that students' difficulty using mathematics in a physics classroom is at least partially an epistemological issue. Students learn about mathematics and physics in very different ways, which contributes to them thinking about knowledge in these two disciplines differently. This may cause them to have difficulty employing the knowledge and skills they learned in a mathematics course in a physics context effectively because they have to switch ways of thinking while solving problems. Thus, students' difficulties in introductory physics courses are not only an issue of content knowledge or mathematics background, but are more complex and related to students' epistemologies about physics and mathematics.

This means that if instructors want to help their students use mathematics in a physics context, we cannot rely only on teaching students the mathematical formalisms needed to solve physics problems. It is imperative that we also pay attention to students' physics and mathematics epistemological resources and their coarser-grained epistemologies about physics and mathematics. Describing the concept of epistemology to students is an easy place to start. A few curricula have been developed in order to explicitly address students' physics epistemology (Redish & Hammer, 2009).

Directly identifying and discussing example epistemological resources that may cause students to struggle with the use of mathematics in a physics context can also be helpful. For example, students tend to think of mathematics as independent of reality and therefore do not check whether their answers to make sense in the real world (i.e., apply the Physical Intuition epistemological resource). When students transition to the more mathematics intensive part of a physics problem, they may not pay attention to whether their answer matches what they would expect in the real world, because they are relying on their mathematical epistemological resources. Instructors could point this out to the students and discuss that even though they using the tools of mathematics, their answer should make sense.

Another possibly strategy is for instructors to solve example problems while specifically pointing out that the answers must match their physical intuition about how the world works. This direct epistemological instruction would address students' underlying epistemological conception that mathematics is isolated from the real world, and would help them to be better poised to use their mathematics knowledge and skills in a physics context. Overall, students' issues with using mathematics in a physics context is not only related to their lack of knowledge and skills but also is related to the students' complex epistemologies about mathematics and physics.

VI. CONCLUSIONS AND IMPLICATIONS

The purpose of this dissertation was to investigate the epistemological resources (Hammer & Elby, 2000) employed by students enrolled in introductory physics courses while solving mathematics and physics problems. Because students do not have articulable access to the epistemological resources they employ, observations of students as they solved problems were conducted. Using internal (Scanlon, 2016) and external (Jones, 2015) a priori operationalizations of epistemological resources as well as emergent coding, thousands of instances of epistemological resource usages were identified. Differences in epistemological resource usage were found between groups of students of varying academic backgrounds (e.g., number of previously completed STEM courses), types of problems solved (e.g., mathematics or physics problems), and content of problems (e.g., energy conservation, graphical kinematics, systems of linear equations, trigonometric functions). This dissertation is comprised of three studies: study 1 investigated the physics epistemological resources students employed as solving physics problems in groups, study 2 investigated the physics and mathematics epistemological resources students employed during office-hour sessions while solving physics and mathematics problems, and study 3 explored the implications for practice from the findings from studies 1 and 2. This chapter provides an overview, summary of the findings, and conclusions for each of the three studies that compose this dissertation along with conclusions across all three studies, delimitations, limitations, implications for research and practice, and suggestions for future research.

Study 1 Overview, Summary of Findings, and Conclusions

The purpose of study 1 was to investigate the physics epistemological resources employed by students enrolled in introductory, algebra-based physics courses while solving physics problems in groups. Participants recorded their discussion about course-assigned physics problems during the laboratory portion of the course. Before the laboratory problem-solving sessions, the participants were trained in group think-aloud procedures (Ericsson & Simon, 1993) and were tasked with giving voice to all of their thoughts as they solved the physics problems in groups. Verbatim transcripts of the participants' discussions were the main data source for this study. Emergent codes were identified as well as an a priori coding scheme that included operationalizations of epistemological resources employed by physics experts was used to determine the physics epistemological resources the participants employed (Jones, 2015).

This study adds to the literature base by investigating the physics epistemological resource usage of multiple introductory physics students as in the extant literature there was only one study which investigated a single student's epistemologies in-depth (diSessa et al., 2002). Jones (2015) studied the physics epistemological resource usage of physics experts while solving novel physics problems while other literature describes the resources framework and posits possible resources. Therefore, this is the only study currently in existence that investigated the epistemological resource usage of students enrolled in introductory physics courses.

Through the implementation of the emergent and a priori coding, a total of 25 physics epistemological resources were identified as the participants solved physics problems. The most commonly employed physics epistemological resource was Peer

Cognitive Awareness which accounted for 22.1% of the total number of physics epistemological resource instances identified. This is most likely an artifact of the data collection process; namely participants were prompted to work and discuss in groups as they solved the problems. The second most commonly employed physics epistemological resource was Mathematical Reasoning—Equation which accounted for 15.5% of the total number of physics epistemological resource instances identified. The high number of instances in which this resource was identified is likely because the problems required the use of equations to solve.

These results indicate that introductory physics students employed the physics epistemological resources identified by Jones's (2015) study in introductory physics students' problem-solving. This adds to the literature base by extending Jones' work to a new population; namely introductory physics students solving the required problems for their course. Through the course of this study, seven new epistemological resources were identified and operationalized. The extant literature scarcely includes operationalizations and real-life examples of epistemological resource usage. Therefore, these results are significantly important because they reinforce Jones' epistemological resource operationalizations and add the physics epistemological new resources to the literature.

The frequency of physics epistemological resource usage data agrees with Hammer and Elby's (2000) description of physics epistemological resources in the sense that students employ a myriad of resources and switch quickly from one resources to the next. In approximately 130 minutes of problem-solving time, over 830 instances of physics epistemological resource usages were identified. This gives an average of 6.4 physics epistemological resources employed per minute which implies participants switched from resource to resource relatively quickly aligning with the extant literature.

After data collection, participant data were grouped based on the participants' number of previously completed mathematics and science courses. The lower/lower (L/L) group included participants with zero to three mathematics class and zero to five science classes, lower/higher (L/H) group included participants with zero to two mathematics classes but with six or more science classes, and the higher/higher (H/H) group included participants with three or more mathematics classes and six or more science classes.

Comparisons of physics epistemological resource usage between these groups of participants were conducted and yielded interesting differences between groups. For example, the Causal Reasoning, Deductive Reasoning, Invoking Authority, Mathematical Reasoning—Graph, and Multiple Representations epistemological resources were employed differently between groups. Specifically, the more science and mathematics experience a student had the more physics epistemological resources they employed in common with experts and vice versa (Jones, 2015). This aligns with the extant literature on epistemological resources—specifically students' physics epistemological resource usages depend on their prior experiences (Hammer & Elby, 2000). Those with more experience in mathematics and science used more resources in common with physics experts while those with less mathematics and science experience used less resources in common with physics experts. Overall, physics epistemological resources were employed differently between participants with varying prior experience in mathematics and science.

Study 2 Overview, Summary of Findings, and Conclusions

The purpose of the study 2 was to determine the similarities and differences in epistemological resource usage of students enrolled in introductory, algebra-based physics courses as they solve mathematics and physics problems. To investigate participants' physics and mathematics epistemological resource usage, participants attended three office-hour sessions over the course of a semester. In each session students solved one physics and one mathematics problem while verbalizing their thinking. The physics problems were taken from the course-assigned homework and the mathematics problems were versions of the physics problems with the background information removed (see Appendix D for the problems solved by the participants). Verbatim transcripts of these office-hour sessions were the main data source for this study.

Using internal (Scanlon, 2016) and external (Jones, 2015) a priori operationalizations, instances of epistemological resource usage were identified as participants solved mathematics and physics problems. In order to best describe the large amount of data collected, an example was selected to ground the discussion in context. Specifically, participant data sampling was driven by usage of signs while solving an energy conservation physics problem. Two students had an inconsistent usage of signs (e.g., the mathematics and physics interpretations of their sign usage did not match) and two students were selected with a consistent usage of signs (e.g., the mathematics and physics interpretations of their sign usages matched).

This study added to the previous literature about epistemological resources by examining the observable problem-solving features the participants were using. While previous work has compared the epistemological resource usages of students with varying academic backgrounds (e.g., study 1), in this study participant data were grouped based on their observable problem-solving features. This study will benefit both the literature base and the practitioners.

The ten most commonly used epistemological resources employed by these four students as they solved physics and mathematics problems were Contrasting Cases, Inductive Reasoning, Invoking Authority, Mathematical Reasoning—Equation, Mathematical Reasoning—Graph, Mathematical Reasoning—Manipulation, Meaning to Symbols, Multiple Representations, Personal Cognitive Awareness, and Physical Intuition. Of note is that the Peer Cognitive Awareness epistemological resource was not identified in this data set, while it was the most commonly employed resource in study 1. The literature base suggests that students' epistemological resource usage should depend highly on the salient features of the context identified by the student (Hammer & Elby, 2002). Therefore, the fact that the Peer Cognitive Awareness epistemological resource was identified frequently as participants worked in groups and was not identified as participants worked alone aligns with this theory. This indicates that the problem-solving context affected the participants' epistemological resource usage. Consequently, special care should be given to the problem-solving contexts for future research because of the highly coupled nature of epistemological resource usage and the problem-solving context.

The usage of the aforementioned epistemological resources was compared between the consistent and inconsistent sign usage groups. Intra-group comparisons yielded data that suggested participants in the same sign usage group employed epistemological resources similarly when solving both mathematics and physics problems. Inter-group comparisons showed the epistemological resources employed by students in each group were different as they solved physics problems but were similar as they solved mathematics problems. This result indicates that participants with differences in the consistency of sign usage employed different physics epistemological resources but similar mathematics epistemological resources.

Participants grouped by the consistency of their sign usage employed different epistemological resources as they solve physics problems but employed similar epistemological resources as they solve mathematics problems. The epistemological resources that participants employ is based on their prior experience and is shaped by their physics and mathematics epistemologies. Because participants' mathematics epistemological resources were similar and their physics epistemological resource usages were different, participants have similar epistemologies about mathematics but different epistemologies about physics. This implies that participants identified based on their sign usage in an energy conservation problem led to groups of students with varying physics epistemological resources usage. Therefore, participants' use of signs in energy conservation problems have an epistemological underpinning and may be separate from their physics and mathematics knowledge and skills.

Prior to this study, there were no investigations of epistemology about mathematics framed with the Epistemological Resources framework. Therefore, this study was an important contribution to the literature base as it investigated the mathematics epistemological resource usage of students enrolled in introductory physics. This study was the first investigation of the mathematics epistemological resources employed by students as they solved mathematics problems.

One of the most salient features of the Epistemological Resources framework is that epistemological resource usage is based on prior experience and context (Hammer & Elby, 2000). It would follow then that students' epistemological resource usage would vary by context and by discipline. The results of this study align with this tenant of the Epistemological Resources framework. Specifically, participants' physics epistemological resource usages were different than their mathematics epistemological resources usages. This also aligns with the general notion of the domain-specificity of epistemology because participants exhibited different epistemologies about physics and mathematics (Muis et al., 2006). Before this study the literature lacked research on the epistemologies held by people about two similar disciplines.

Study 3 Overview, Summary of Findings, and Conclusions

The purpose of study 3 was to explore the implications of the first two studies for classroom practice. The main emphasis of the third study was the need for teachers to be aware of the physics and mathematics epistemological resources employed by students' while problem-solving and give this issue attention in their teaching. Differences in participants' epistemological resources employed while solving physics and mathematics problems were discussed. Namely, all of the reasoning epistemological resources (Analogical Reasoning, Causal Reasoning, Deductive Reasoning, Inductive Reasoning, and Mechanistic Reasoning) were only employed by participants while they solved physics problems. Similarly, differences in number of instances for numerous epistemological resources were identified. Because mathematics and physics epistemological resources usage is grounded in the students' epistemologies about mathematics and physics, students have different epistemologies about physics and mathematics and these differences may affect their use of mathematics in a physics context. Educators must be of aware of these aspects of the students in their classes and pay attention to them in their teaching.

The main argument of this study is that student difficulties in introductory physics courses could be due to their conceptualizations about using mathematics in a physics context. This is an epistemological issue which is supported by the differences in epistemological resource usage identified as students solved physics and mathematics problems. Teachers should not only focus on teaching students the mathematical formalisms required for physics problem-solving, but also should pay attention to students’ epistemologies about physics.

The results of study 1 and 2 imply that increasing students’ experience in mathematics and science can help to broaden their epistemological resource usages. Therefore, classroom teachers should be aware that their students’ may have epistemological resource activation patterns that can hinder their success in introductory physics. Furthermore, they should help to promote students’ epistemological development in their courses along with teaching the content of the course.

Conclusions across Studies

Across all three studies, epistemological resources were identified in two different problem-solving contexts (working in lab in group versus working individually in office-hours). The results from the first two studies show that epistemological resource usage can be determined through observation of students’ problem-solving. These studies built on Jones’ (2015) work and replicated a similar study to his with the new population of students enrolled in introductory, algebra-based physics. An important contribution to the literature base is the descriptions and operationalizations of the seven new epistemological resources. Only Jones' (2015) study and this dissertation have distinct operationalizations and real-life examples of epistemological resources in the literature.

Different epistemological resources were employed by participants in the differing problem-solving contexts (e.g., group work versus individual work). For example, the most commonly employed physics epistemological resource in the group problem-solving session during the first study was Peer Cognitive Awareness (22.1% of total instances identified) whereas this resource was not identified at all during individual problem-solving in the second and third studies. This implies that the problem-solving context impacted the epistemological resources employed by participants. Therefore, the notion that epistemological resource usage is highly context-dependent aligns with this result (Hammer & Elby, 2000). As students perceive different salient features in the differing problem-solving contexts they activate and employ different epistemological resources. This has implications for research in that the problem-solving context under study should be carefully chosen as it will dramatically impact students' epistemological resource usage.

Another cross-cutting theme throughout the studies is that the identification of differences in epistemological resource usage between participants. These differences were identified between participants with varying academic backgrounds (e.g., number of previously completed mathematics and science courses), physics problem-solving approaches, (e.g., sign usage during energy conservation problem), and type of problem solved (e.g., physics or mathematics problems). One tenant of the epistemological resources theoretical framework is that epistemological resource usage is shaped by prior experience, participant identification of salient problem features, and context in which the epistemological resources are employed (Hammer & Elby, 2000). These results align with theory because differences in epistemological resource usage were found along these same parameters. Epistemological resource usage is highly dependent upon the specific of the context identified by students.

These studies also lead to the conclusion that students' difficulties in introductory physics may have an epistemological component. Not only do students have difficulties with lacking mathematics knowledge and skill but they also have difficulties in using their mathematics knowledge and skills in a physics context. The students' epistemologies about physics and mathematics differ as seen by their epistemological resource usage patterns as they solve physics and mathematics problems. This implies that students' difficulties in introductory physics may be an epistemological issue—therefore practitioners should not only focus on teaching the mathematics skills but should also pay attention to students' conceptions about knowledge in physics and mathematics.

One open question is how the epistemological Beliefs (Schommer, 1990) and Epistemological Resources (Hammer & Elby, 2000) relate to one another. It is theorized that epistemological resources are finer-grained thank epistemological beliefs but how close in grain-size they are remains unknown. Also, how the epistemological resources compare and/or compare with the epistemological beliefs is also uninvestigated.

Delimitations

An overall delimitation for this dissertation is related to the fact that the primary researcher also was the instructor of record for the courses in which the data were collected. Due to the primary researcher's understanding of the epistemological resources framework, some of the resources were discussed indirectly in class and the framework shaped how these courses were taught and administered. For example, during the laboratory sections of the course where the data were collected, the instructor encouraged and actively promoted students asking the instructor questions. Therefore, this could have led to an increase in the number of Invoking Authority codes due to the course structure instead of due to some inherent difference in the participants' "natural" epistemological resource usage.

Another overall delimitation for this dissertation was the space allowed for each study was dictated by the publications. Unfortunately, only a carefully chosen and representative set of findings were able to be discussed due to manuscript length restrictions. Study 1 was limited to 5,000 words, study 2 was limited to 3,500 words, and study 2 was limited to 2,000 words. Other findings (e.g., comparisons of epistemological resource usage between groups of varying academic background, incoming attitudes and beliefs, and incoming conceptual understanding) and study information can be found in the appendices of this dissertation.

Study 1 Delimitations. A delimitation of the first study is related to the purpose of the study which was to identify and characterize introductory physics students' physics epistemological resources and their associated usage patterns. This study was intended give a macroscopic view of the physics epistemological resources used by students enrolled in introductory physics while they solve many different types of physics problems. This leaves the details of the source of the differences between participants' physics epistemological resource usage ambiguous. The differences between participants could be due to the nature of the physics content of the problem, the nature of the mathematics content of the problem, the different difficulties and types of the problems, the timing during the semester in which the problem was solved, the group dynamics between the participants in groups, the differences in prior experience both in mathematics and physics as measured more finely than by previous number of courses completed, the differences in motivation level from day to day, and numbers other possible reasons.

A second delimitation arose from how the data were collected for this study; namely in a laboratory setting as students solved physics problems in groups. The data were collected during group think-aloud sessions (Ericsson & Simon, 1993) where participants were asked to discuss and work with their partner to solve physics problems. Due to this data collection technique, the participants were required to work as a group. This could have increased the number of Peer Cognitive Awareness codes compared to what would be present if the participants were not specifically prompted to work together. Both of the introductory physics courses in which the data were collected were also taught such that symbolic solutions were required for all problems involving numbers. This fact was emphasized to the students from the start of the first course to the end of the second course. The students are made aware that their grade depends upon their derivation of a symbolic solution for all such problems. Therefore, students are trained to view the physics problems from a mathematical approach and to value the mathematical equations of physics. This could have artificially inflated the number of instances of the Mathematical Reasoning—Equation, Mathematical Reasoning—Manipulation, Equation, and Calculation epistemological resources.

Study 2 Delimitations. A delimitation of study 2 is related to the setting in which the data were collected; namely the office-hour sessions. While participants were solving the problems, the primary researcher allowed them to work on their own until they asked for help or could not proceed. Then the primary researcher would step in and assist the student. Therefore, during most of the problem-solving sessions the student was assisted by the primary researcher. This may have affected the epistemological resources that the participants employed due to the highly context-dependent nature of epistemological resource usage (Hammer & Elby, 2002).

Another delimitation of study 2 was the mathematics problems chosen for the participants to study. The mathematics problems were versions of the physics problem where the background information had been removed. While the physics problems were typical problems assigned in the course, the mathematics problems required the same mathematics knowledge and skills, and were the same complexity, they lacked context. Because of the highly context-dependent nature of epistemological resources, the context-free mathematics problems could have influence the epistemological resources the participants employed. If instead the mathematics problems were contextualized (e.g., real-world word problems), the participants may have employed different epistemological resources. Future research should address this issue by varying the context of both the mathematics and physics problems.

Limitations

A limitation of this dissertation is the quality of the video and audio recordings that were the main data corpus. The first component of this limitation relates to the quality of the audio and video recordings. The audio recordings in the first study were collected by the students. Therefore, at times it was difficult to hear the discussions of the participants. The video recordings for the second and third studies were collected in the office of the primary researcher. Periodically there were other students in the office next door which created background noise.

The second component of this limitation relates to the quality of discussion recorded. During the first study participants were recorded as they solved the required problems for their course during the laboratory class period whereas during the second and third studies students were given extra credit for discussion of their thought processes of problems required for the course. Both of these methodological features were intended to motivate students to do their best and include a rich discussion. Unfortunately, not all participants had the in-depth and rich discussions the study settings were intended to foster.

Implications

The next two sections will discuss the implications for the three studies in this dissertation both for practice and for research.

For Practice. Because of participants' differing epistemological resource usage based on their prior academic background, identification of salient problem features, and problem-solving strategies, educators should pay attention to students' epistemologies about physics and mathematics. Students not only have difficulties in using mathematics and physics simultaneously due to a lack of mathematics knowledge and skill as is intimated by the extant literature, there is also an epistemological component. Educators should explicitly explicate the nature of epistemology about physics and mathematics and focus on assisting students with shaping their epistemological resources activation (and associated inhibition) patterns.

These studies have shown that student epistemological resource usage is highly context and experience dependent. Also, one of the tenants of the Epistemological Resources framework is that the purpose of education is mold students' epistemological resource activation (and inhibition) patterns such that students employ epistemological resources at appropriate times (Hammer & Elby, 2002). Therefore, educators should expose students to a myriad of contexts in order to help students build their epistemological resource patterns. If students do not have experience with particular problems, then they will not have a well formed activation pattern for those problems. Educators should allow students the opportunity to build their epistemological resource activation patterns by exposing them to problems of varying contexts and surface features.

For Research. These three studies indicated that introductory, algebra-based physics students' epistemological resource usages can be identified as they solve physics and mathematics problems in groups. Using an external (Jones, 2015) and internal (Scanlon, 2016) a priori operationalization of epistemological resources along with emergent coding, numerous epistemological resources employed by these participants were identified. The emergently identified epistemological resources have now been operationalized and added to the literature base. Also, because participants' epistemological resource usages widely varied based on nuanced differences in problems, problem-solving context, and social interactions, future researchers take extreme care when designing the aforementioned study components.

This dissertation determined the scope of epistemological resources employed by students enrolled in introductory, algebra-based physics courses as they solved physics and mathematics problems and laid the foundational work of the characterization of these students' epistemologies about mathematics and epistemologies about physics.

Recommendations for Future Work

In future studies, research should focus on continuing to investigate the epistemologies about physics and about mathematics of students enrolled in introductory physics courses. Because of the highly context-dependent nature of epistemological resource activation, these studies should be replicated in other environments such as in office-hour sessions working in groups and homework sessions formed naturally by students. Future studies should also focus on extending this research to other populations. This study focused on introductory, algebra-based physics students at a small, private, liberal-arts school. Future studies might examine students majoring in physics or enrolled in upper-division physics courses at varying types of institutions. Also, comparisons of the physics epistemological resource usage of physics experts and novices should be conducted. A lingering question is how does epistemological resource usage vary by problem-solving context and what are the salient features identified participants that shape their epistemological resource activation?

The differences in epistemological resource usage should also be investigated further. For example, differences between students of varying CLASS and FCI pre-test scores should be conducted. Are there differences in epistemological resource usage based on students' academic background as predicted in theory? Also, differences by content of the physics and mathematics problems and time in semester should be investigated further. Will students' epistemological resource usage vary by the content of the problems solved (e.g., kinematics problems versus energy conservation problem)? What is the effect of a physics course on students' epistemological resource usage? Do students' epistemological resource usage patterns change over the course of a semester? Finally, differences in epistemological resource usage of novice physics students and physics experts should be conducted. As indicated in study 1, how do students' epistemological resource usage compare with experts.

Another interesting avenue of future research is to determine the purpose of epistemological education. Barzilai and Chinn (2017) argue that the purpose of epistemological education should not be to induce developmental change in students' epistemologies or change students' epistemological to be more expert like as the endpoints of these trajectories are nebulous and highly discipline and context-dependent. Instead, they argue that the goal of epistemic education should be to give students' the potential to use their epistemology aptly in a myriad of circumstances. Future research using Barzilai and Chinn's (2017) framework of epistemic education should be conducted using the epistemological resources lens.

Another avenue for future research is related to the boundary between the subconscious epistemological resources participants employ and the conscious metacognitive thought about epistemology. Where is the boundary? How do students transition from unconscious utilization of an epistemological resource to a conscious, metacognitive usage? This also has implications for classroom practice, specifically, how can we assist our students in developing more appropriate resource usage when they cannot consciously think about these resource usage?

Finally, future work should develop an intervention in order to assist students that inappropriately apply their epistemological resources (e.g., a targeted epistemic educational intervention). This intervention should be designed to be used in a class and should target students' inappropriate resource usage in order to help them be more successful in the future.

Summary

This chapter focused on explicating the overall conclusions of this dissertation along with the specific conclusions of each of the three studies composing this dissertation. First, an overview of the dissertation and each of the three studies were presented. Next, a summary, overview of findings, and conclusions for each of the three studies were presented.

The following sections were the delimitations and limitations of this dissertation. The delimitations section covered methodological decisions that were controlled by the researcher that affected the generalizability, scope, and boundaries of the dissertation. The limitations section covered the limits of the generalizability and reliability of the dissertation that were not able to be controlled by the researcher. Next, implications for both research and practice of the dissertation were discussed. Finally, the recommendations for future research in their area were identified and discussed.

APPENDIX SECTION

APPENDIX A—Study 1 Physics Problems Solved by Participants

APPENDIX B—Study 1 Epistemological Resource Operationalizations and Examples

APPENDIX C—Study 2 Interactive Observation Protocol

APPENDIX D—Study 2 Physics and Mathematics Problems Solved by Participants

APPENDIX E—Study 2 Epistemological Resource Operationalizations and Examples

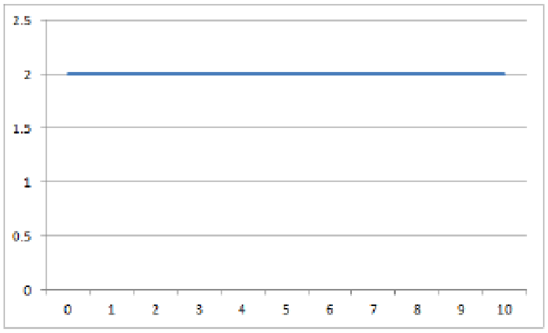
APPENDIX F—Study 2 Inter-Rater Reliability Documents

APPENDIX A—Study 1 Physics Problems Solved by Participants

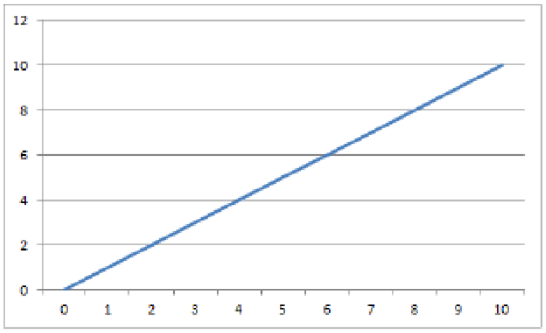
Physics 1 Questions

Lab 1—Graphing Motion

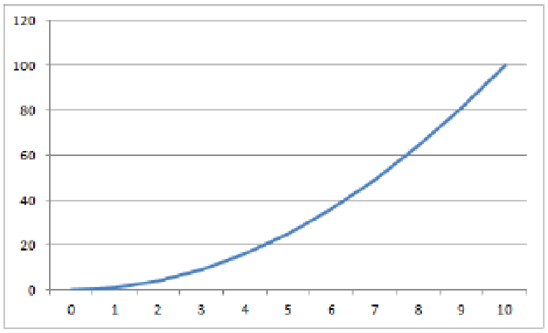
Use the following graphs to answer all parts of question three.



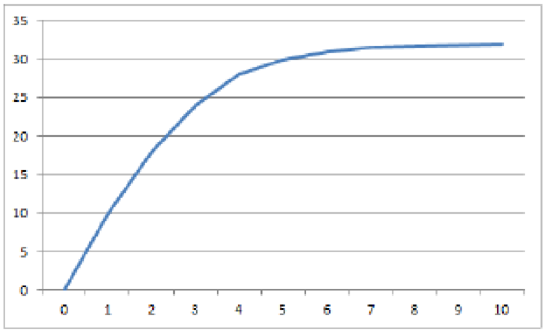
a: Graph A



b: Graph B



c: Graph C



d: Graph D

A) If the graphs shown are position versus time, which graph represents an object at rest?

B) If the graphs shown are position versus time, which graph represents an object moving with a constant, non-zero velocity?

C) If the graphs shown are position versus time, which graph represents object with the largest displacement?

D) If the graphs shown are position versus time, which graph represents the object with the largest velocity from $t=9.0$ s to $t=10$ s?

E) If the graphs shown are velocity versus time, which graph represents an object moving at a constant velocity?

F) If the graphs shown are velocity versus time, which graph represents an object whose velocity is changing constantly as a function of time?

Lab 2—Projectile Motion

Bella, fed up with physics, throws her physics textbook off the edge of a 55 m high cliff. She throws her book at a 30° angle above the horizontal with a speed of 15 m/s.

A) What is the books maximum height?

B) How fast is the book moving at its maximum height?

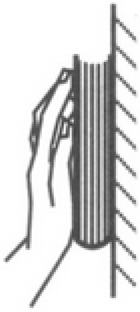
C) How long is the book in the air?

D) How far from edge of the cliff does the book land?

E) How fast is the book moving just before it hits the ground?

Lab 3 –Forces

You are holding your physics book against the wall by pressing on it as shown in the figure below.



A) You are pressing hard enough so that the book doesn't move. Draw a free-body diagram for the book, being sure to identify all the forces that might be acting on the book. For each force state what object is causing it and what object is feeling it?

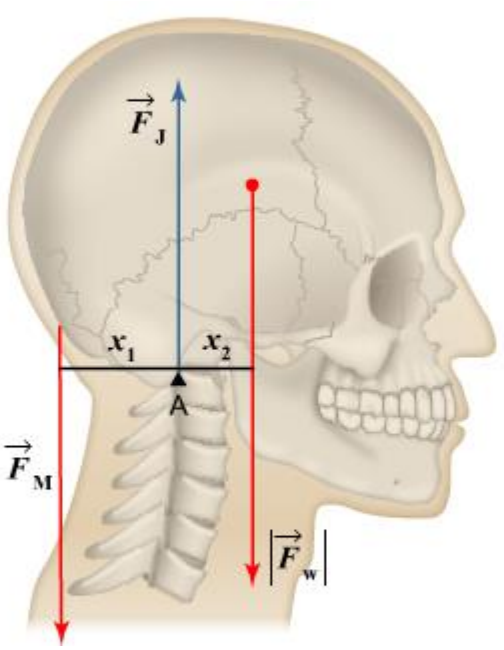
B) What relations are there among the forces in your diagram? That is, which forces or sums of forces have to be equal? How do you know?

C) You begin to get tired and the book begins to slide down. As it starts to slide, you respond so it slides down at a constant velocity. How do each of the forces you have identified change from their magnitudes in part A)? Explain how you know.

D) If the book has a mass of 2.00 kg, the coefficient of friction between the sliding book and the wall is 0.40, how hard do you have to press on the book if it is sliding down with a speed of 2.00 cm/s?

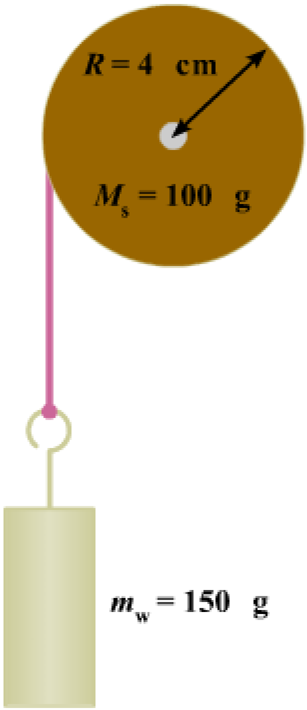
Lab 4—Torque

Even when the head is held erect, as in the figure below, its center of mass is not directly over the principal point of support (the atlanto-occipital joint, point A). The muscles at the back of the neck should therefore exert a force to keep the head erect. If the head weighs 55 N, calculate the force exerted by the jaw, F_J. As defined in the picture, use the following values: x_1=5.10 cm and x_2=2.50 cm.



Lab 5—Rotational Dynamics

A 150-g weight is tied to a piece of thread wrapped around a spool, which is suspended in such a way that it can rotate freely. When the weight is released, it accelerates toward the floor as the thread unwinds. Assume that the spool can be treated as a uniform solid cylinder of radius R = 4 cm and mass M_s = 100 g. Find the tension in the thread and the magnitude of the acceleration of the weight as it descends. Assume the thread has negligible mass and does not slip or stretch as it unwinds.



Lab 6—Momentum

When jumping straight down, you can be seriously injured if you land stiff-legged. One way to avoid injury is to bend your knees upon landing to reduce the force of the impact. Suppose you have of mass m and you jump off a wall of a height h.

A) With what speed will you hit the ground? Assume you simply step off the wall so your initial vertical velocity is zero. Ignore air resistance.

B) Suppose that the time interval starting when your feet first touch the ground until you stop is Δt. Calculate the (average) net force acting on you during that interval.(Plug the symbolic solution from part A) into your answer for this part.)

C) Suppose h = 1 m. If you land stiff-legged, the time it takes you to stop may be as short as 2.0 ms, while if you bend your knees, it might be as long as 0.10 s. Calculate the average net force that would act on you in the two cases. The average mass of an adult male is approximately 62.0 kg.

Lab 7—Work and Energy

In a Newton's cradle, 5 balls of substantial mass are suspended from a framework. When you pull one of the balls away from the group and release it, the ball's collision with the group causes a single ball to bounce away from the far side. Similarly, when two balls are raised, two balls bounce away. A student says "this has to happen to conserve momentum." But another student asks, "When two balls are dropped, why couldn't a single ball come out of the other side twice as fast?" This would satisfy conservation of momentum, but it never happens. Why not?

Lab 8—Standing Waves on String

A banjo D string is 0.69 m long and has a fundamental frequency of 294 Hz. Shortening the string (by holding the string down over a fret) causes it to vibrate at a higher fundamental frequency. Where should you press to play the note F-sharp, which has a fundamental frequency of 370 Hz?

Physics 2 Questions

Lab 1—Reflection and Refraction

When a light ray transitions from a medium of low index of refraction to a medium of high index of refraction, does the light ray generally bend toward the normal or bend away from the normal? Explain.

Lab 2—Image Formation

A slide projector needs to create a 98 cm high image of a 2.0 cm tall slide. The screen is 300 cm from the slide. Assume that it is a thin lens.

A) What focal length does the lens need?

B) How far should you place the lens from the slide?

C) What is the magnification of the lens?

Lab 3—Electric Fields

A molecule of DNA is 2.17 μm long. The ends of the molecule become singly-ionized negative on one end, positive on the other. The helical molecule acts like a spring and compresses 1.00 percent upon becoming charged. Determine the effective spring constant of the molecule.

Lab 4—Gel Electrophoresis

In all cells it is easier for positive potassium ions (K^+) to flow out of the cell than it is for negative ions. As a result, there is a negative charge on the inside of the cell membrane and positive charge on the outside of the membrane, much like a capacitor. A typical cell with a membrane thickness of 7.60 nm.

A) Find the capacitance of a square patch of membrane 1.00 μm on a side, assuming that there is only air in the membrane.

B) The actual structure of the membrane is a layer of lipid surrounded by layers of a polarized aqueous solution and layers of water as shown in the figure below. Taking account of this structure, find the capacitance of a square patch of membrane of 1.00 μm on a side.

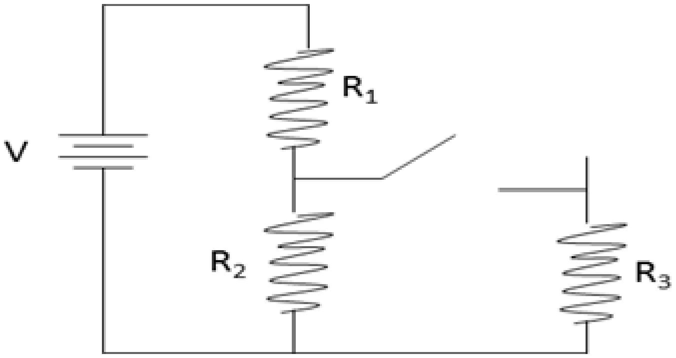
Lab 5—Circuits and Ohm's Law

A thermistor is a device whose resistance varies with temperature in a well-defined way. A certain thermistor has a resistance of 2.8 kΩ at 20 °C and 0.39 kΩ at 70 °C. This thermistor is used in a water bath in a lab to monitor the temperature. The thermistor is connected in a circuit with a 1.5 V battery, and the current is measured. What is the change in current in the circuit as the temperature rises from 20 °C to 70 °C?

Lab 6—Kirchhoff's Laws and Resistors

A) Calculate the equivalent resistance when 1) the switch is open and 2) when the switch is closed.

B) Calculate the current through each resistor when the switch is closed. The potential difference of the battery is 6 V, R_1=10 Ω, R_2=100 Ω and R_3=1.0Ω.



Lab 7—Magnetic Fields

What current is required in the windings of a long solenoid that has 1,000 turns uniformly distributed over a length of 0.400 m in order to produce a magnetic field of magnitude 1.00×10^{-2} T at the center of the solenoid?

Lab 8 –Flux and Faraday's Laws

A 12.0 cm diameter loop of wire is initially oriented perpendicular to a 1.5 T magnetic field. The loop is rotated so that its plane is parallel to the field direction in$0.20 s. What is the average induced emf in the loop?

APPENDIX B—Study 1 Epistemological Resource Operationalizations and Examples

The Calculation epistemological resource is an emergent code that emerged through participants' words in the audio recordings. The Calculation epistemological resource is identified when students were discussing or carrying out a calculation. This corresponds to participants trusting the knowledge generated through following appropriate mathematical calculation techniques. This resource was identified when participants were 1) carrying out a symbolic or numeric calculation or 2) discussing how to or the implications of a mathematical calculation. An instance where the calculation epistemological resource was identified was while students Ana (low/low) and Andrea (low/high) discussed how to calculate the torque on a human head. Shown below is an excerpt of their discussion:

1 Ana: Okay so torque two is equal to

2 Andrea: its fifty five Newtons, okay. Point zero two fives times fifty five. Okay so th-torque two is one point seven five

3 Ana: meters times fifty five Newtons times one

4 Andrea: seventeen

5 Ana: Oh it's awesome!

6 Andrea: Aren't we awesome. [sound of button pushing on calculator]

7 Ana: Point two fifty at fifty five Newtons did you get thirteen point seventy five?

In line 1 of this transcript Ana initiates the calculation by saying the torque of interest is "equal to". Then Andrea picks up the calculation in line 2 describing the numbers and how they are related in the equation which continues on line 3. Finally in line 7 Ana indicates the result of their calculation (this line also indicates the use of the Peer Cognitive Awareness epistemological resource which is discussed below). In this instance, Ana and Andrea performed a calculation and trusted that their use of accurate mathematical technique will lead to a trustable answer. The Calculation epistemological resource was identified a total of 48 times in the data and appeared in 8 of the 9 problems analyzed.

Another epistemological resource identified was an established code called Causal Reasoning. Jones (2015) describes Causal Reasoning as reasoning in which a cause including an action and effect can be identified with a link between the two. In order for Causal Reasoning to be identified an agent responsible for the cause, an action word related to the cause, an effect, and a link between the cause and the effect must be identified (Jones, 2015). Causal Reasoning was identified in the excerpt below:

1 Caitlin: You have static friction don't you?
2 Andrea: Um….
3 Caitlin: Which is keeping the book like on the wall?

In this except Caitlin (H/H) and Andrea (L/L) are discussing the forces exerting on a book held in place on a wall by a hand. The cause identified is "you have static friction", the effect is "keeping the book like on the wall", the link is "which is keeping", and the action word is "keeping". The Causal Reasoning epistemological resource was identified only a total of 4 times in 4 separate audio recordings.

Another important resource identified in the participants' words was the Consistency code. Jones defines the Consistency epistemological resource as a general code that describes the coherence between an identified model and either observation or a prediction based on that model. In order to identify this resource either 1) a model and a prediction based on that model must be identified with a statement that a prediction using the model should (or should not) match observation or check for consistency with another prediction or 2) an observation must be identified and an attempt to align this observation with a model must be observed (Jones, 2015). Consistency is a common epistemological resource used by experts and therefore if novice physics students use this resource it could imply a high level of reasoning or problem solving skills in the student. Shown below is an excerpt of a discussion between Caitlin (H/H), Andrea (L/L), and the course instructor about how the model (constant velocity) should affect behavior of a sliding book:

1 Instructor: Is your object moving?
2 Caitlin: If its sliding down
3 Andrea: Sure.
4 Caitlin: the wall…
5 Andrea: Yeah.
6 Caitlin: Right?
7 Instructor: Correct. Is it accelerating?
8 Caitlin: It is…it's not. Its
9 Andrea: Oh…
10 Caitlin: It doesn't-it has a constant acceleration doesn't it?

11 Andrea: And it’s sliding down.

12 Instructor: It’s at a constant velocity [emphasis on “velocity”]

13 Caitlin: It has a constant velocity

14 Instructor: So what does that mean about acceleration?

15 Caitlin: That means that the accelera-oh okay. Hold on.
[sound of erasing]

16 Andrea: What?

17 Caitlin: It has a constant velocity which means the acceleration is increasing.

In this excerpt the instructor is leading through the students through a consistency line of reasoning. The model identified by Caitlin is an acceleration of zero. Then Caitlin predicts that the object should move at constant velocity and then predicts that the acceleration should be increasing. While the second prediction is not correct, this line of reasoning still constitutes an invocation of the Consistency epistemological resource. The Consistency epistemological resource was identified a total of 7 times in 4 separate audio recordings.

The most commonly employed physics experts while solving novel problems is the Contrasting Cases epistemological resource (Jones, 2015). This resource describes how experts draw upon and focus on the similarities and differences between two or more contexts to generate knowledge (Jones, 2015). In order for an excerpt to be coded as Contrasting Cases either 1) two cases can be identified or 2) a continuous spectrum of cases can be identified and a comparison between cases must be present (Jones, 2015). A clear example of the Contrasting Cases resource is in use came while Christina (L/L) and

Ana (L/H) were discussing how to solve for the forces acting on a book held at rest on a wall by a hand. An excerpt of their discussion is shown below:

1 Christina: I wonder if we’re allowed to use our notes from class…

2 Ana: I think we are.

3 Christina: Hmm? You think we can?

4 Ana Yeah.

5 [sound of backpack unzipping] [sound of papers hitting table]

6 Ana: It was negative weight plus force of stan-theta plus oh yeah plus the static friction

7 Christina: So F sine of theta was…what was that? [pause] Oh that was just the overall force.

8 Ana: Mmm hmm

9 Christina: No wait what was the

10 Ana: F max, right?

11 Christina: That was the push and we don’t have a push on this one.

12 Ana: Well the hand though

13 Christina: Oh that is the normal force.

In this example Christina takes out her notes on a similar problem done in class (lines 1-5). Then in lines 6-7 Ana and Christina starts reading off from the notes. The similar problem done in class is the primary case and the problem they were working on in lab is the secondary case. In line 11 Christina is identifying a difference between the cases; in the in class problem there was a push force acting on the object whereas in the problem they were working during the audio recording there was not a push force. Therefore, this excerpt shows an example of when the Contrasting Cases epistemological resource was used (this excerpt also shows the Invoking Authority, Equation, Mathematical Reasoning 1, and Peer Cognitive Awareness epistemological resources).. The Contrasting Cases epistemological resource was identified a total of 30 times in 7 separate problems.

Another resource identified in the participants’ problem solving was Deductive Reasoning which is defined by Jones (2015) as “a form of logic where one begins a line of reasoning from an idea that acts as a premise and reasoning logically from this premise to some sort of conclusion” (p. 72). This resource was coded if there was a premise, a conclusion based on that premise, and a link between these two. The Deductive Reasoning resources was identified a total of 15 times in 5 different problems. In the excerpt, the Instructor, Andrea (L/L), and Thomas (L/L) were discussing an object colliding with the ground:

1 Instructor: Is your object in free fall?
2 Thomas: Yes.
3 Andrea: Yeah, well its
4 Instructor: Yes
5 Andrea: in free fall-oh god.
6 Instructor: What does that mean
7 Andrea: I know that.
8 Instructor: about the acceleration?
9 Thomas: Its nine point eight meters per second.
10 Andrea: Its nine point eight.
11 Instructor: Wa-and its constant.

In lines 66 and 68 Andrea identifies that the object of interest is in free fall after being prompted by the instructor. This acts of the premise and the conclusion is that the acceleration is nine point eight (lines 72-74). And the link between the premise and the conclusion comes in line 69 and 71. Therefore this instance shows the use of the Deductive Reasoning epistemological resource.

One of the most commonly occurring epistemological resource was Equation. This resource was coded 116 total instances across 8 of the 9 audio recordings. The Equation epistemological resource originally was coded as part of the Multiple Representations epistemological resource from Jones' coding scheme (2015). The Multiple Representations epistemological resource as operationalized by Jones (2015) includes participants employing any representation other than verbal communication. These representations may include graphs, diagrams, equations, etc. Through the emergent round of coding, it was determined students commonly invoked or reasoned with equations. Therefore, encompassing equation as well as other representations (e.g. diagrams, graphs) would mask the actual amount of times that the students invoked equations. Due to this fact, an emergent code called Equation was identified when participants were invoking, stating, or employing an equation. A sample instance of where the Equation epistemological resource was identified is below:

1 Sophia: I total [pause] is equal to I one. [short pause] Um…delta V B is equal to I total times R E Q closed. [pause] So I total is equal to R E Q closed. Plus R three.

In this instance Sophia (H/H) is describing an equation that will solve for the current flowing through a circuit. Due to the fact that Sophia is invoking an equation to solve the problem, the Equation epistemological resource was identified.

The Multiple Representations epistemological resource was identified when the participants used a representation other than verbal communication and/or equations. This epistemological resource was identified in a total of 18 instances in 7 different audio recordings. An instance of where the Multiple Representations epistemological was identified is shown below:

1 Andrea: Mmm [pause] how will we find acceleration?
2 Caitlin: So I’m gonna draw [pause]
3 Andrea: A [unintelligible]
4 Caitlin: Yeah
5 Andrea: Graph times
6 Caitlin: So if you have velocity versus times

In this instance Caitlin (H/H) and Andrea (L/L) invoked an equation in order to determine the acceleration of an object. While this strategy did not lead to a fruitful outcome, the students still invoked an equation allowing for the identification of the Equation epistemological resource.

Another established resource identified in the data was the Experimentation resource which is defined by evidence of experimentation during the instance, directly talking about a hypothesis or result derived from personally performing an experiment, or discussing a new experiment to could be conducted to test a hypothesis. This resource was not commonly applied and only appeared a total of 3 instances in 1 problem. In the sample instance below, Brenda (L/H) is directly quoting a result of the laboratory she just completed:

1 Brenda: Okay um…[pause] Well we already know velocity is independent of mass.

In this instance Brenda directly quotes the results of the experiment she just conducted and therefore this instance was coded as Experimentation.

An interesting emergent epistemological resource was dubbed If It’s Given It Must Be Used. This resource was coded when participants expressed the idea that if something was given in the problem statement, then it must be used in their answer to the problem. This resource was coded a total of 7 times in 3 separate problems. The excerpt below exemplifies the usage of If It’s Given It Must Be Used epistemological resource by Caitlin (H/H):

1 Caitlin: O-oh oh h oh! That’s what you’re saying. [sound of erasing] But we never used the velocity. So that’s
2 Instructor: We didn’t!
3 Caitlin: Is that okay?
4 Ana: It was just an extra
5 Caitlin: Oh okay that’s why I thought we were wrong cause we weren’t using it.

In this excerpt Caitlin is voicing her concern over not using velocity in her final answer because it was given in the problem statement. Previous in the audio recording, her concern derailed her work on this problem due to her identification that the velocity was given but not used in her final answer.

Another established code identified in the data was Inductive Reasoning which is defined as logic that is based on an observation as a premise. In order for an instance to be coded as Inductive Reasoning there must be a premise based on an observation, a conclusion derived from that premise, and a link showing the connection between the two (Jones, 2015). This resource was only identified in a total of 4 instances across 3 problems.

1 Instructor: Okay so if you look at it um the torque of your weight of your head-if you just like if you just go slack
2 Ana: So like that
3 Instructor your head goes down, right so its rotates this way
4 Ana: Down
5 Instructor: And when you pull your muscles you bring your head up
6 Ana: Up
7 Instructor: So
8 Ana: So that’s why the-the
9 Instructor: They are rotating your head in opposite directions
10 Ana: the muscles one would be up-the positive
11 Andrea: Opposite

In this instance, watching the Instructor rotate their head is an observation that acts as a premise. The conclusion derived from that premise appears in lines 9 and 10 where Ana

(L/L) identifies that the torques would be exerted in the opposite directions and the link between the conclusion and premise is in line 7.

A commonly employed resource by novice physics students is Invoking Authority (Bing & Redish, 2008). This code was emergent and was identified when the participants invoked or were attempting to invoke a definition, equation, idea, etc. from an authority source. The authority sources varied widely from the textbook, to a result from a problem done in class, to the instructor, and more. The Invoking Authority epistemological resource was identified in all 9 audio recordings for a total of 75 instances. There were two separate types of Invoking Authority cases; the first where the participants directly quoting an authority source and the second where the participants attempting to invoke an authority source by asking the source a question. Below is an excerpt showing Andrea (L/L) and Caitlin (H/H) employing the second form of the Invoking Authority epistemological resource:

1 Andrea: It’s like ten centimeters in one meter. Right?
2 Caitlin: I think that’s a hundred [pause] centimeters in a meter. Try Google it.

In this excerpt Andrea and Caitlin where discussing the proper conversion from centimeters to meters. Since they could not remember if there were one hundred or ten centimeters in a meter, they invoking the authority of Google to look up the conversion. In this instance the participants “asked” Google to tell them the correct conversion thereby invoking Google’s authority. Commonly throughout the audio recordings the participants' invoked the authority of the instructor (possibly due to the teaching style of the instructor; see Delimitations section for more on this).

An interesting resource that was identified only two times in the audio recordings was the Knowledge as Fabricated Stuff epistemological resource. This resource first appears in Hammer and Elby's (2000) discussion of the epistemological resource framework. They describe the Knowledge as Fabricated Stuff as a resource typically used by children to explain how they know something as being derived from some other source material. The identification of this resource from audio recordings of undergraduate introductory physics students was surprising due to the fact that it was originally described as a resource employed almost exclusively by children. Below is a quintessential example of this resource's use:

1 Ana: How do we know-because we know. Because we're smart. [laughs]

2 Christina: Yeah [laughs

In this excerpt Ana (L/L) is justifying her answer to a forces problem by the statement "we know because we know". Ana is possibly saying that she knows her answer to be correct because of what she has learned in the course. Another interpretation could be that she doesn't know why she knows her answer and is attempting to make a joke to save face. This is where follow-up questioning will take place in future research.

Another resource from the established coding is Knowledge from Direct Observation which is the resource associated with participants trusting knowledge that they have personally observed. This resource is identified when there is evidence that the participant is looking at the experiment, if they refer to seeing or looking at something in the experiment, or if they reference data gathered from an experiment they personally carried out (Jones, 2015). This resource was only identified in a total of 10 instances in 5 separates problems. In the sample excerpt below, Chris (H/H) and Ana (L/H) are interpreting a group of position versus time graphs in order to determine which represents an object with the largest displacement:

1 Chris: The graphs shown are position versus time what if-which graph represents an object with the largest displacement? [Chris is reading the question verbatim.]

2 Ana: Displacement.

3 Chris: [sound of sucking air into mouth with pursed lips]

4 Ana: For sure not A because it’s not even moving so it’s constant.

5 Chris: Its ah look here on the side. [pause] Its gonna be C cause there’s just

6 Ana: the intervals are much greater

7 Chris: Well it-yeah and it moves from zero to a hundred.

In line 5 Chris refers to looking at the side of the graph. Therefore, he is deriving knowledge from directly observing the graphs and is therefore employing the Knowledge from Direct Observation epistemological resource.

Limitations of Model is an extremely important resource while solving physics problems due to the model nature of the discipline (Jones, 2015). Therefore, a resource related the limitations of the models derived is important for building expertise. The Limitations of Model epistemological resource was identified a total of 8 instances across

3 audio recordings. In order to code for the Limitations of Model resource there must be a model and statement about the mismatch between the model and the scenario being discussed.

1 Ana: Like that?
2 Instructor: So now you need to solve for F J
3 Ana: But F J is not there
4 Instructor: It's not! So we need another equation.

In this instance Ana (L/H) is expressing that the model she and her partner (Andrea, L/L) had derived did not include the variable that they were attempting to solve for. Therefore, the model identified was not complete in order to solve this problem. This is evidence of the use of the Limitations of Model epistemological resource.

A resource that connects mathematical formalism to meaning is the Mapping Meaning to Math epistemological resource (Redish & Kuo, 2015). This resource is identified when participants talk about the relationship between the mathematical formalism and the meaning behind the mathematical formalism.

1 Chris: Um…that makes sense cause this is gonna be constant for the air
2 Rachel: Right.
3 Chris: no matter what. Or if it changes then, anyways-so, say you have a constant number like that
4 Rachel: Okay
5 Chris: and I divide by a big number like that one, that'd make
6 Rachel: Right it'll go small

7 Chris: that and then if I divide it by a smaller number, I get bigger number so, as this

8 Rachel: Right

9 Chris: gets bigger, this is gonna get smaller.

10 Rachel: Right so then its gonna go toward.

11 Chris: Mmm hmm [indicating agreement]

12 Rachel: Okay.

13 Chris: Cause you go toward then your angle gets smaller.

In this exchange Chris (H/H) is reasoning about how light transitioning from a material of low index of refraction to a material of high index of refraction. In lines 1-7 he is using proportional reasoning to determine that changing the index of refraction would make the angle smaller. The he maps the mathematical answer (smaller number) to the physical meaning (as the angle gets smaller, the light ray will bend toward the normal due to the angle’s definition). Chris is directly interpreting his mathematical answer as it articulates in the physical situation of the problem. This epistemological resource is important in introductory physics courses due to the highly entangled nature of mathematics within the course. Mapping Meaning to Math was identified a total of 37 times in 7 different audio recordings.

An important epistemological resource to physics as a discipline is Mathematical Reasoning (Jones, 2015). In this operationalization, Jones (2015) described five criteria for the Mathematical Reasoning epistemological resource including talking about an equation, using and/or manipulating an equation, using or interpreting a graph, discussing the relationship between or form of a relationship between variables. Many of the problems the participants solved during the audio recordings required students to mathematically solve for a symbolic and numeric solution in the problem, the Mathematical Reasoning epistemological resource as defined by Jones (2015) was too broad. Therefore, the Mathematical Reasoning resource was broken down into three different categories (Mathematical Reasoning 1, 2, and 3) that commonly occurred throughout the audio recordings. Mathematical Reasoning 1 includes taking about a mathematical equation, relationship between variables, or the form of a relationship. In the excerpt below, Ana (L/H) is discussing the physics behind a Newton's cradle:

1 Ana: So momentum is…P final equation P initial right?

In this example, Ana is talking about the conservation of momentum equation (P represents momentum). This excerpt was obviously coded for Mathematical Reasoning 1 but was also coded as Invoking Authority (due to the fact that Ana is regurgitating the definition of momentum conservation either from the textbook or from her notes), Equation (due to the fact that she is discussing a mathematical equation), and Peer Cognitive Awareness (due to the fact that Ana is asking her partner if her definition of momentum is correct thereby showing her awareness of her partner's cognitive abilities; more on this resource is described below).

The Mathematical Reasoning 2 epistemological resource was identified when the participants talked about manipulating an equation. Manipulating an equation included a calculation in this coding scheme. This resource was identified in all but one audio recordings for a total of 79 instances. In the example below, the instructor and Ana (L/H) are describing how to solve a torque equation for the variable of interest:

1 Instructor: Right-just like you said right here sine of theta goes to one so both of these are just one. [short pause]

2 Andrea: So just write in there

3 Ana: So could then you divide by this to get F M and then plug it in over here?

4 Instructor: Boom boom! Exactly.

5 Ana: Okay and then do the same thing for F W and plug it in

Ana described the mathematical manipulations she would employ on the mathematical expression relating torques on a human head. Since she is describing the manipulation of mathematical expressions this is an example of the Mathematical Reasoning 2 epistemological resource.

The Mathematical Reasoning 3 epistemological resource is recognized when participants are making, describing, or interpreting a graph. One of the problems the participants solved during the audio recordings specifically asked them to interpret graphs. Therefore one of these audio recordings had a significantly higher number of Mathematical Reasoning 3 instances. In total, there were 23 instances of the Mathematical Reasoning 3 resource across 2 audio recordings. For an example, the excerpt below Caitlin (H/H) spontaneously invokes a graph to assist in her problem solving:

1 Andrea: How will we find acceleration?

2 Caitlin: So I’m gonna draw [pause]

3 Andrea: A table right? Like that

4 Caitlin: Yeah

5 Andrea: Graph times

6 Caitlin: So if you have velocity versus time

7 Andrea: And we have the [short pause] point zero two meters per second so that’s

8 Caitlin: So we have our base

In line 5 Andrea (L/L) states that Caitlin is drawing a graph in order to calculation the acceleration of the object of interest. In line 6 Caitlin states the graph is a velocity versus time graph and in lines 7 and 8 they start interpreting the graph in order to calculation the acceleration. This is an example of the Mathematical Reasoning 3 epistemological resource because the participants drew and interpreted a graph to assist their problem solving. This was the only instance in all of the audio recordings where the participants used a graph without being directly prompted in the problem statement.

Another emergent epistemological resource was called Meaning to Symbols which is identified by participants transcribing the meaning of the problem statement into symbols or when participants interpret the meaning of the symbols defined in the problem. In both of the courses where the audio recordings were collected the instructors emphasized the importance of defining a list of symbols (called a list of Knowns) at the start of each problem. Therefore, the number of instances of the Meaning to Symbols epistemological resource was likely affected by this fact. In total 21 instances of this resource were identified across 5 separate audio recordings. In the snippet below, Ana (L/L) and Andrea (L/H) are starting a problem asking to calculate the forces and torques exerted to keep a head erect:

1 Ana: X one so we know knows X one is equal to five point ten centimeters so then we need to change that to meters. Five point ten [sound of pushing buttons on calculation]

2 Andrea: Is point, what point zero five one?

3 Ana: Mmm hmm. [indicating agreement]

4 Andrea: Point zero five one.

5 Ana: Meters.

6 Andrea: And X two is

7 Ana: That’s X one. X two equals

8 Andrea: Point zero two five

9 Ana: These in meters

10 Andrea: meters. So you’re writing down the knowns right?

11 Ana: Mmm hmm. [indicating agreement]

12 Andrea: And head weight is okay, we’ll add in the mass. Head weighs-weight of head, sixty fi-fifty five Newtons. Okay. And we’re trying to find the force J. Can I put question mark?

In line 1 Ana explicitly references writing a list of knows in which she defined the quantities given in the problem with variables. In lines 6-8 Ana and Andrea are defining the distance measurements and in line 12 Andrea defines the unknown quantity by setting its variable name equal to a question mark. This process is highly emphasized throughout both introductory physics courses.

Another established epistemological resource was Mechanistic Reasoning. In order for an instance to be coded as Mechanistic Reasoning, there must be an initial phenomenon, a final phenomenon, and a process linking these two phenomena (Jones, 2015). Only 5 instances of this resource were identified in 2 separate problems. In the sample excerpt below, Andrea (L/L) and Ana (L/H) discussed the torque exerted on a human head:

1 Andrea: Of the musc-torque of the muscle equals minus torque of the weight equals zero, so then you’re gonna add torque of the weight to both sides with torque of the weight so then torque of the muscle [short pause] equals

2 Ana: Its zero

3 Andrea: torque of the weight because if not your head would go downward back.

The initial phenomenon is the torque of the muscles minus the torque of the weight is equal to zero (line 1). The final phenomenon is that the head does not go downward. Therefore this instances shows the implementation of the Mechanistic Reasoning epistemological resource.

The Peer Cognitive Awareness epistemological resource captures how participants work together to solve problems (Jones, 2015). It is recognized when participants ask another person for clarification, ask another person a question or for input, referencing what another person said, and/or attempting to explain something that another person indicated they did not understand (Jones, 2015). Due to the fact that during the audio recordings participants were specifically prompted to discuss and work with their group member, there is a possibility for more Peer Cognitive Awareness codes than would occur under different problem solving circumstances. The Peer Cognitive Awareness epistemological resource was the most commonly identified resource for a whopping total of 185 instances and was also identified in every single audio recording.

1 Andrea: So…[pause] acceleration equals…

2 Thomas: V initial is zero. Okay so it'd be one half nine point eight T squared, equals H. [sound of paper sliding around] [pause]

3 Andrea: What's the equation for…um, a [short pause] are we using-are we answering A or…are we using

4 Thomas: Well

5 Andrea: the information to see

6 Thomas: Hold on hold on hold on, height, the wall equals to [sound of writing] [sound of erasing] so that's how you find the height of the wall. [pause]

7 Andrea: Why'd you use four point nine?

8 Thomas: It's one half of nine point eight.

9 Andrea: Okay.

In lines 3 and 7 Andrea (L/L) asks Thomas (L/L) two different clarifying questions. This implies that this excerpt has two separate instances of the Peer Cognitive Awareness epistemological resource being employed.

A similar epistemological resource to Peer Cognitive Awareness is Personal Cognitive Awareness (Jones, 2015). While Peer Cognitive Awareness is to capture participants working together and their awareness of their team member's cognitive process, Personal Cognitive Awareness is to measure students' metacognition. Metacognition, a broad topic, generally is a person's ability to be consciously aware of their thinking and thought process. Personal Cognitive Awareness is identified when participants explicitly reference what they are thinking about as related to themselves (Jones, 2015).

1 Instructor: So the graphs shown are position versus time.
2 Chris: Oh!
3 Instructor: Position versus time
4 Chris: I don’t know why I was thinking velocity versus time.
5 Instructor: So if it was velocity versus time it’d be way harder
6 Chris: Yeah my-I don’t know why I was thinking that

In lines 4 and 6 Chris (H/H) explicitly referencing that personal nature of what he was thinking (indicated by the use of the word “I”) as well as that he didn’t understand why he was thinking what he was thinking. This is a clear usage of the Personal Cognitive Awareness epistemological resources.

Another epistemological resource was emergent and was titled Physical Intuition (Kuo & Redish, 2015). This resource was identified in 2 instances in2separate audio recordings. Physical intuition is identified when participants invoke their understanding of how the world works based on their prior experiences in the world. A goal of many introductory physics courses is to help students build a correct physical intuition about how the world works (Kuo & Redish, 2015). In the excerpt below, Ana (L/H) using he intuition about an object at rest:

1 Ana: I think the graph A would represent an object at rest because you have [pause] it’s at two and it’s not moving right?

In this excerpt, Ana is using her intuition about what it means to be at rest (e.g. the object is not moving). Since Ana was drawing upon her understanding about the world from her previous experience, she was invoking the Physics Intuition epistemological resource.

The Plausibility epistemological resource is employed when the person is considering the possibility of applicability of multiple models. This epistemological resource is identified when there is discussion of a model and an explicit indication that the model may be appropriate or not (Jones, 2015). The Plausibility epistemological resource was identified a total of 3 instances in 2 different problems. In the excerpt below, Thomas (L/L) and Andrea (L/L) were discussing how to find speed:

1 Thomas: To find your speed [emphasis on the word "speed"] [pause] you do [pause]

2 Andrea: I don't know, the speed…[short pause] equals change in [pause] change in X over time.

In line 2 of this excerpt, Andrea states the velocity equation which is a model and explicitly states that she is not sure if this is the appropriate equation. Therefore, this excerpt shows the usage of the Plausibility resource.

One instance of the Relative Value of Knowledge being used was identified. The Relative Value of Knowledge resource captures experts' ability to identify what information or knowledge is valuable under different circumstances. Thus it makes sense that only once instance of the epistemological resource was identified as the participants are novice, introductory physics students. In the excerpt below,

1 Andrea: Ummm what was the other one Mu, mu s

2 Caitlin: Mu static but we're not

3 Andrea: But we don't know that

4 Caitlin: super worried about that right [emphasis on "super"]

In line 4 Caitlin (H/H) is stating that the static friction (indicated by Mu s which is the coefficient of static friction) is not important while solving this problem. Caitlin is essentially stating that the static friction knowledge has relatively low value in solving this problem thereby employing the Relative Value of Knowledge.

The final epistemological resource identified was Sense Making which is identified when participants discuss a model, hypothesis, and/or idea with a statement that this model, hypothesis, and/or idea does, does not, or should make sense (Jones, 2015). The Sense Making epistemological resource was only identified in one instance in this data set. In the following instance Caitlin (H/H) discussed how a particular idea does not make sense:

1 Caitlin: So F K equals zero. No that doesn't make sense [trails off]

In this excerpt Caitlin came to a conclusion about the static friction force acting on an object and determined that this idea did not make sense thereby employing the Sense Making epistemological resource.

APPENDIX C—Study 2 Interactive Observation Protocol

Campus: Texas Lutheran University

Interviewer: Erin Scanlon

Location: Erin Scanlon's Office (Moody 221)

Interviewee:

Date:

Start Time:

End Time:

Notes:

Interview Sections Utilized; Degree of Fidelity to Protocol (Check if Used/Applicable):

_____ **Pre-Interview**

Degree of Conformity to Protocol ____%

_____ **Topic Domain I: Math Problem**

Degree of Conformity to Protocol ____%

_____ **Topic Domain II: Career Task**

Degree of Conformity to Protocol ____%

_____ **Topic Domain III: Physics Problem**

Degree of Conformity to Protocol ____%

_____ **Conclusions**

Degree of Conformity to Protocol ____%

_____ **Follow Up/Thank You Email**

Degree of Conformity to Protocol ____%

_____ **Other Topics Discussed:**

_____ **Documents/Artifacts Collected**: Copy of Student Work on math and physics problem

_____ **Post Interview Comments/Concerns/Irregularities:**

_____ **Length of Interview:**

Pre-Interview

Turn on video camera.

A. Welcome Script: Welcome [insert participant's name] and thank you for your participation! I am Erin Scanlon the primary researcher for this study.

B. Introductory Narrative: The purpose of this study is to determine the epistemologies about mathematics and physics of introductory physics students. This session should last approximately 20-60 minutes but you will be given as much time as you need to solve the problems. Depending on the session, the need for follow up questions may present itself. Thank you so much for your participation!

C. Informed Consent: As we discussed in class, your participation in this study is completely voluntary. You may skip any questions or ask that any part of any question be excluded from the research study. You may stop participating anytime without penalty including a penalty in class. Remember you will receive extra credit for attending these specific office hour activities and solving the assigned problems regardless of your participation in this study. In order to receive extra credit, you must attend all three of the specific office hour sessions and solve the assigned problems.

This study should involve minimal risk and discomfort to you. If you feel uncomfortable at any time and would like to stop, indicate this intention to me and we will stop immediately without penalty. The probability of harm and discomfort should not be any greater than your daily work as a student. Risks may include emotional discomfort from answering interview questions. If you remember, we went over this when you signed your consent form in class.

Do you have any questions for me? Do I have your consent to participate in this study? (Wait for response. If yes, continue. If no, stop interview recording and delete recording.)

D. Other Permissions: To facilitate documentation and analysis, this session will be video recorded with your permission. I will not show this video to anyone without express permission from you (the interviewee). Do you have any questions for me? If you agree to this session being video recorded, please read and sign the video recording consent form. (Wait for response. If sign, continue. If does not sign, stop and delete recording. Continue with interview without video recording.)

E. Interview Overview: During this time, we will cover three separate tasks; a mathematics problem, a career task, and the assigned physics problem. You will be given as much time as you need to complete these three tasks.

F. Introduction/Rationale: The purpose of this interview is to observe you solving math and physics problems. Unfortunately I cannot see into your head and know what you thinking. So in order for me to know what you are thinking I need you to say everything you are thinking. Here is a little bit of information about what's called a Think-Aloud which is what I would like you to do. (Show the Think-Aloud Protocol Info Sheet.) So solve the problems like you would normally. I just want to see how you solve problems in your normal circumstances. Feel free to ask me questions while you are working. Think aloud protocol

G. Goals & Expectations: My goal for this study is to observe you solving math and physics problems. Therefore, I expect you to solve the three problems. Please make sure to verbalize all your thoughts. The results of this study will be presented in academic journals and at academic conferences. Do you have any questions, comments, concerns, jokes, ideas, or limericks before we get started?

Topic Domain I: Math Problem [Counterbalance order of math and physics problems]

1. Please read this problem aloud. (Give participant the mathematics problem.)

2. What do you think about this problem? [Covert Objective: Asking about initial conceptions of problem.]

[Follow-Up Probes: difficulty, problem solving strategy, seen this type of problem before]

3. Go ahead and solve the problem. Don’t forget to say everything you are thinking

[Covert Objective: Prompting participate to employ think-aloud protocol.]

[Follow-Up Probes: point out relevant features of problem (from teaching experience), ask to clarify what they mean (from research experience)]

4. (Allow participant to finish mathematics problem.) How did that go?

[Follow-Up Probes: difficulty, relation to physics]

5. Is there anything else you would like to say about this problem?

Topic II Domain: Time Management [Covert Objective: Distractor Task #1]

1. What classes are you taking?

2. How do you manage your time with these classes?

[Follow-Up Probes: Outside of school activities, daily schedule, completing assignment]

3. How well is this strategy working for you?

[Follow-Up: Happiness level, completion of tasks, work-life balance]

4. Is there anything else you would like to share about your time management strategy?

Topics II Domain: Student Check-in [Covert Objective: Distractor Task #2]

1. How are things going this semester? How are things going? How's school?

[Follow-Up Probe: campus involvement, small talk about campus related issues, outside of this course]

2. Tell me about how you can improve your study habits.

[Follow-Up Probe: Time, patterns, place]

3. Is there anything else you would like to tell me about your study habits?

Topic Domain II: Summer Plans [Covert Objective: Distractor Task #3]

1. What are you summer plans?

[Follow-Up Probes: Family trips, job, classes]

2. Is there anything else you would like to tell me about your future goals?

Topic Domain III: Physics Problem [Counterbalance order of math and physics problems]

1. Please read this problem aloud. (Give participant the physics problem.)

2. What do you think about this problem? [Covert Objective: Asking about initial conceptions of problem.]

[Follow-Up Probes: difficulty, problem solving strategy, seen this type of problem before]

3. Go ahead and solve the problem. Don’t forget to say everything you are thinking [Covert Objective: Prompting participate to employ think-aloud protocol.]

[Follow-Up Probes: point out relevant features of problem (from teaching experience), ask to clarify what they mean (from research experience)]

4. (Allow participant to finish physics problem.) How did that go?

[Follow-Up Probes: difficulty, relation to physics]

5. Is there anything else you would like to say about this problem?

Conclusions:

Before we conclude this session, is there anything else you would like to share?

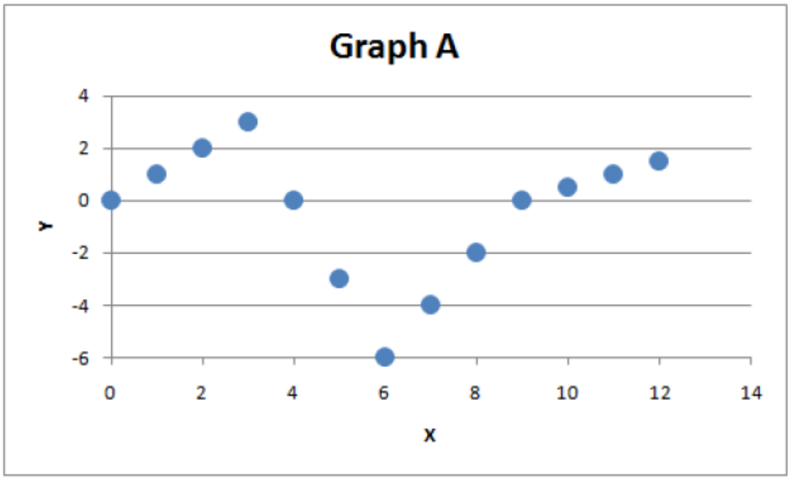
Post Interview Comments and/or Observations:

PHYS 141 - Kinematics Problem

1. Instructions
   - Make sure to say everything you are thinking while solving the problem. Please don't just write down your answer but instead discuss your thoughts about the problem and the solution. The goal is to see/hear your thinking process while solving problems.
   - Remember a think-aloud is saying everything that comes to your not and is not silently writing your answers. Feel free to refer to the Think-Aloud Information Sheet for ideas.
2. Shown below is a graph of Y versus X, called Graph A.

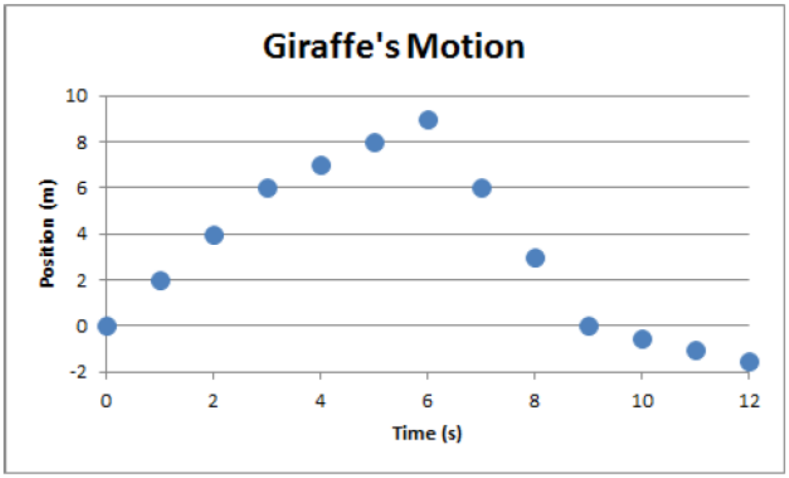
   A) Calculate the slope of each piece-wise linear segment.

   B) Produce a graph of the slope of Graph A over the same X interval.



PHYS 141 - Kinematics Problem

1. Instructions
   - Make sure to say everything you are thinking while solving the problem. Please don't just write down your answer but instead discuss your thoughts about the problem and the solution. The goal is to see/hear your thinking process while solving problems.
   - Remember a think-aloud is saying everything that comes to your not and is not silently writing your answers. Feel free to refer to the Think-Aloud Information Sheet for ideas.
2. The position versus time graph shown below is for a reticulated giraffe running in the Masai Mara. Sketch the corresponding velocity versus time graph for this giraffe.



PHYS 141 - Problem 2

1. Instructions
   - Make sure to say everything you are thinking while solving the problem. Please don't just write down your answer but instead discuss your thoughts about the problem and the solution. The goal is to see/hear your thinking process while solving problems.
   - Remember a think-aloud is saying everything that comes to your not and is not silently writing your answers. Feel free to refer to the Think-Aloud Information Sheet for ideas.
2. Given the two equations below, x and y are variables while A, B, and C are constants.

$$Ay - BC = 0 \qquad y - x = 0$$

   A) Solve the equations for x only in terms of the constants.

   B) If $A = 0.3$, $B = 1$, $C = 10$, calculate x.

PHYS 141 - Problem 2

1. Instructions
   - Make sure to say everything you are thinking while solving the problem. Please don't just write down your answer but instead discuss your thoughts about the problem and the solution. The goal is to see/hear your thinking process while solving problems.
   - Remember a think-aloud is saying everything that comes to your not and is not silently writing your answers. Feel free to refer to the Think-Aloud Information Sheet for ideas.
2. You are holding your physics book against the wall by pressing on it as shown in the figure below.
   (a) You are pressing hard enough so that the book doesn't move. Draw a free-body diagram for the book, being sure to identify all the forces that might be acting on the book. For each force state what object is causing it and what object is feeling it?
   (b) What relations are there among the forces in your diagram? That is, which forces or sums of forces have to be equal? How do you know?
   (c) If the book has a mass of 2.00 kg, the coefficient of friction between the sliding book and the wall is 0.40, how hard do you have to press on the book if it is sliding down with a speed of 2.00 cm/s?

Physics 141 - Problem 3

1. Instructions
   - Make sure to say everything you are thinking while solving the problem. Please don't just write down your answer but instead discuss your thoughts about the problem and the solution. The goal is to see/hear your thinking process while solving problems.
   - Remember a think-aloud is saying everything that comes to your not and is not silently writing your answers. Feel free to refer to the Think-Aloud Information Sheet for ideas.
2. In the following equation A, B, C, and D are constants. solve for θ in terms of these constants.

$$ABC\sin(\theta) = \frac{1}{2}AD^2$$

PHYS 141 - Problem 3

1. Instructions
   - Make sure to say everything you are thinking while solving the problem. Please don't just write down your answer but instead discuss your thoughts about the problem and the solution. The goal is to see/hear your thinking process while solving problems.
   - Remember a think-aloud is saying everything that comes to your not and is not silently writing your answers. Feel free to refer to the Think-Aloud Information Sheet for ideas.
2. Generic Physics Woman is enjoying a day of skiing on a slope that is angled at θ above horizontal. She starts at the top of the slope that is 120 m long. If she starts at rest on the frictionless ramp and reaches a speed of 10 m/s at the end of 120 m, what is the angle θ of the slope? Use energy conservation to solve.

APPENDIX E—Study 2 Epistemological Resource Operationalizations and Examples

1. Analogical Reasoning

I. Operationalization: From Jones, 2015

1. Can identify a physical scenario or object that serves as the analog.

2. Can identify a physical scenario or object that serves as the target.

3. Presence of a phrase that links the two in such as way that meaning is transferred from source to target without saying that the target literally is the source. The phrase can also be negative and link the two in such a way that meaning cannot be transferred.

(All three must be met)

II. Example from my Dissertation Study (Ophelia 2, page 8)

STUDENT: Kind of yeah. So kind of like, like you wouldn't say it's the hand muscle force like -I don't -like if your hand could

INTERVIEWER: Something like that.

STUDENT: Like it's the hand that like

INTERVIEWER: Yes.

STUDENT: let's say we have The Force like in Star Wars right? Like you wouldn't say like it's The Force that's on it. [Laughs]

INTERVIEWER: That's exactly -no nono but that's a really good analogy.

STUDENT: Right? It's -it's the hand that's doing it.

2. Attention to Novelty

I. Operationalization: From Jones, 2015

1. Discussion of some intuitive expectation not being met.

2. Explicitly mentioning that something is interesting.

3. Identifying that something is confusing.

(Only one must be met)

II. Example from my Dissertation Study (Joan 2, page 31)

STUDENT: Um, I don't know not having to combine like X and Y factors and have all this really long. [moves hands apart from each other to indicate long]

INTERVIEWER: Okay. [nods head]

STUDENT: Then I always get like confused on the signs and like positive and negative.

3. Causal Reasoning

I. Operationalization: From Jones, 2015

1. Identification of an agent(s) (object or phenomenon) responsible for the cause.

2. A phenomenon that is the effect.

3. A consequential link between the two OR that the two are not causally related.

4. Utterance containing the cause should have some kind of action word.

(All four required)

II. Example from my Dissertation Study (Kylie 2, page 12)

STUDENT: Uh cause it's like one Force like it's the Force Normal or the Applied Force was stronger it would cause it to move in that direction.

4. Contrasting Cases

I. Operationalization: From Jones, 2015

1. Either:

A) A primary case and secondary case can be identified.

B) A continuous set of cases can be identified

2. Evidence that there is a comparison between the primary and secondary cases.

(Both required)

-Doesn’t include question at end of session where participants were forced to compare mathematics and physics problems

II. Example from my Dissertation Study (Denise 2, page 6)

STUDENT: [short pause] It's just a typical Force Problem although it's a little like kind of turned because now you're pressing on something [representing pushing something horizontal]. So rather than it being on the floor [representing pushing something downward] it's now pushed up against the wall. But other than that everything's kind of turned but.

5. Deductive Reasoning

I. Operationalization: From Jones, 2015

1. A statement based on prior knowledge that acts as a premise.

2. A conclusion derived from that premise.

3. A linguistic link showing evidence that the conclusion is based on the premise.

(All three required)

II. Example from my Dissertation Study (Sofia 2, page 8-9)

STUDENT: They should have a net force of zero? [raises an eyebrows]

INTERVIEWER: [Agreeing] And so if you look in your X direction there [points towards student’s paper] you have your weight force downwards.

STUDENT: [Agreeing] [nods head]

INTERVIEWER: Can that sum to zero?

STUDENT: [shakes head no]

INTERVIEWER: No? So what does that tell you?

STUDENT: There's a force going up [points upward]

6. Experimentation

I. Operationalization: From Jones, 2015

1. Actually carrying out an experiment.

2. Directly talking about a hypothesis that was supported or disproved by performing some experiment or the results from personally doing an experiment.

3. Discussing a new potential experiment that they could do and how you could test your hypothesis from the experiment with intent or evidence of taking data.

(Only one must be met)

II. Example from my Dissertation Study (Jessica 2, page 21)

INTERVIEWER: Okay? So why don't you put your pencil down just for a sec? [student puts her pencil on the desk] So [claps her hands together and starts rubbing them together] rub your hands together gently [student stars rubbing her hands together slowly] versus [interviewer pushes her hand together hard and moves them back and forth] push them together really hard.

STUDENT: [Agreeing]

INTERVIEWER: Which one do you experience a greater friction force?

STUDENT: When you push really hard.

7. If It’s Given, It Must Be Used

I. Operationalization: From Comps Study

1. A statement that something was given in the problem and therefore it must be used.

II. Example from my Dissertation Study (Jaime 2, page 30-31)

STUDENT: Oh so then if I plug that in up here -if I plug in force of gravity for force of friction, then I can get -and I also plug in force applied for force normal, I don't know what that would do for me. Because I have to find a way to relate the velocity to all of this.

INTERVIEWER: Okay. And -and why do you think that? I'm just curious.

STUDENT: Well because, I don't know. I just feel like because it's like a specified velocity you'd have to find a way to make that two point zero -or I guess zero point zero two like into the equation.

8. Inductive Reasoning

I. Operationalization: From Jones, 2015

1. A statement based on observations that acts as a premise.

2. A conclusion derived from that premise.

3. A linguistic link showing evidence that the conclusion is based on the premise.

(All three must be met)

II. Example from my Dissertation Study (Jessica 2, page 5)

INTERVIEWER: what do we know about the forces acting on it?

STUDENT: They all equal each other.

INTERVIEWER: They all equal each other. Tell me why.

STUDENT: Or they cancel each other out.

INTERVIEWER: Okay.

STUDENT: Because it's not -if they didn't cancel each other out it would be moving in a certain direction.

9. Invoking Authority

I. Operationalization: From Comps Study

1. Participants invoked or were attempting to invoke a definition/equation/idea from an authority.

2. Must include either:

A) A reference to the authority source.

B) The name of the definition/equation/idea that is being invoked.

(Both must be met)

II. Example from my Dissertation Study (Juanita 3, page 4)

INTERVIEWER: And why is it okay to define that as H equals zero?

STUDENT: Uh cause it doesn't matter, where you define it.

INTERVIEWER: Why?

STUDENT: All I remember in class we did that problem –or the one on the other homework like where we had like the two different distances but we didn't need that like we only needed one.

10. Knowledge from Direct Observation

I. Operationalization: From Jones, 2015

1. A reference to “seeing” something happening in the experiment.

2. A reference to “look” at the experiment.

3. Evidence of prolonged eye contact with the experiment as a statement about the experiment is being made related to observations.

4. Reference to data that has been gathered or an experiment that has been performed and the fact that it was personally gathered and observed by the participants.

(Only one must be met)

II. Example from my Dissertation Study (Brooke 1, page 15)

STUDENT: It looks weird to like start up here [pointing to graph on paper] and then just jump down. Like, cause when we when we did it with the motion detectors

INTERVIEWER: [nods head] In lab.

STUDENT: we can't just jump down. And so it kind of like curves and

INTERVIEWER: [Agreeing] So, in real life, it has to have that curving?

STUDENT: Yes, so, in real life, it doesn't have, the slope is undefined.

11. Limitations of Model

I. Operationalization: From Jones, 2015

1. A model.

2. Some statement that references a mismatch between the model and the current situation. This can be:

A) A statement that the model is inappropriate for this situation.

B) A statement that the model is only an approximation of the situation.

C) Statement that model needs modification to match current situation.

(Both must be included)

II. Example from my Dissertation Study (Brooke 1, page 17)

STUDENT: Yeah, so we're just simplifying the giraffe's motion.

12. Mathematical Reasoning—Equation

I. Operationalization: From Comps Study

1. Participants discuss a mathematical equation, relationship between variables, or the form of a relationship.

II. Example from my Dissertation Study (Lauren 2, page 26)

STUDENT: Yeah F W on B equals F H on B. [writing on her paper]

13. Mathematical Reasoning—Graph

I. Operationalization: From Comps Study

1. Participants discuss making, describing, or interpreting a graph.

II. Example from my Dissertation Study (Marie 1, page 1)

STUDENT: So for the first slope it goes from zero to positive three -so the rise is three and then it's over a period of three seconds so the run is three.

14. Mathematical Reasoning—Manipulation

I. Operationalization: From Comps Study

1. Participants discuss manipulating an equation.

2. Participants conduct a calculation.

(Only one must be met)

II. Example from my Dissertation Study (Ophelia 3, page 17)

STUDENT: And since we solved for H here we can plug that into [writing on her paper] that equation so theta equals arcsine V final squared over two G over X.

15. Meaning to Symbols

I. Operationalization: From Comps Study

1. Participants transcribe the meaning of the problem statement into symbols.

2. Participants interpreting the meaning of symbols defined in a problem.

3. Writing a list of knowns.

(Only one must be met)

II. Example from my Dissertation Study (Lauren 2, page 8)

STUDENT: So since the book wants to slide down, the static friction would oppose motion in the upwards direction. So we'll call that um, F K –I mean F S.

16. Mechanistic Reasoning

I. Operationalization: From Jones, 2015

1. An initial phenomenon.

2. A final phenomenon.

3. A process linking the initial and final phenomenon.

(All three must be met)

II. Example from my Dissertation Study (Sofia 2, page 15)

STUDENT: Because if the push force was greater I guess maybe you would push the book like [pushes hand horizontally] through the wall.

17. Multiple Representations

I. Operationalization: From Jones, 2015

1. Evidence of some type of representation of information that is not verbal communication (such as a diagram) being used or discussed in some way.

-Must be non-verbal and non-equation.

-If problem is about a graph or Free Body Diagram, does not count.

II. Example from my Dissertation Study (Brooke 2, page 27)

INTERVIEWER: No. [shakes head] So if your Velocity is constant that mean –so delta V final

STUDENT: Oh, okay.

INTERVIEWER: minus initial would always be zero.

STUDENT: I'm thinking of the wrong graphs. Okay

INTERVIEWER: Okay. Which graphs were you thinking of?

STUDENT: Cause like when, like that -so this is Velocity and time Graph [draws a velocity versus time graph with a linear line with a positive slope] this is Constant, so that means Acceleration in times would be, it could be here, it could be here, it could be here. [draws an acceleration versus time graph on her paper with three horizontal lines: positive, zero, and negative]

18. Personal Cognitive Awareness

I. Operationalization: From Jones, 2015

1. A statement made by an individual where they make reference to what they are thinking (or not understanding) and explicitly reference the personal nature of what they are thinking.

II. Example from my Dissertation Study (Jessica 2, page 2)

STUDENT: I'm just trying to think of another term to like [mimicking writing over her paper]

INTERVIEWER: Mmm!

STUDENT: call that.

19. Physical Intuition

I. Operationalization: From Comps Study

1. Participants invoke their understanding of how the world works based on their prior experience in the world.

2. Experience must be related to some physics and/or mathematics ideas.

(Both must be met)

II. Example from my Dissertation Study (Joan 2, page 15)

STUDENT: Okay. And then when I'm using my coefficient of friction that's gonna be kinetic.

INTERVIEWER: Correct because the book is sliding. [emphasis on ‘because’]

STUDENT: Because it's sliding.

20. Relative Value of Knowledge

I. Operationalization: From Jones, 2015

1. Discussion of an idea/model/hypothesis.

2. An individual making some comment about the importance or usefulness of that idea.

(Both must be met)

II. Example from my Dissertation Study (Jaime 1, page 1)

STUDENT: The giraffe doesn't really pertain to the problem

INTERVIEWER: Okay. [nods head]

STUDENT: I'd say so whether it was

INTERVIEWER: What do you mean?

STUDENT: Whether it was like a giraffe or a racecar that doesn't really matter when you're sketching, the um, [reading off his paper] velocity versus time graph.

INTERVIEWER: Okay.

STUDENT: So you kind of just have to pay more attention to the numbers and figure out what's important to you and what's not as you -well I guess before you start actually analyzing [short pause] his position compared to the time.

21. Sense Making

I. Operationalization: From Jones, 2015

1. Discussion about some idea/model/hypothesis.

2. A statement related to whether or not that idea/model/hypothesis does, doesn't or should somehow make sense.

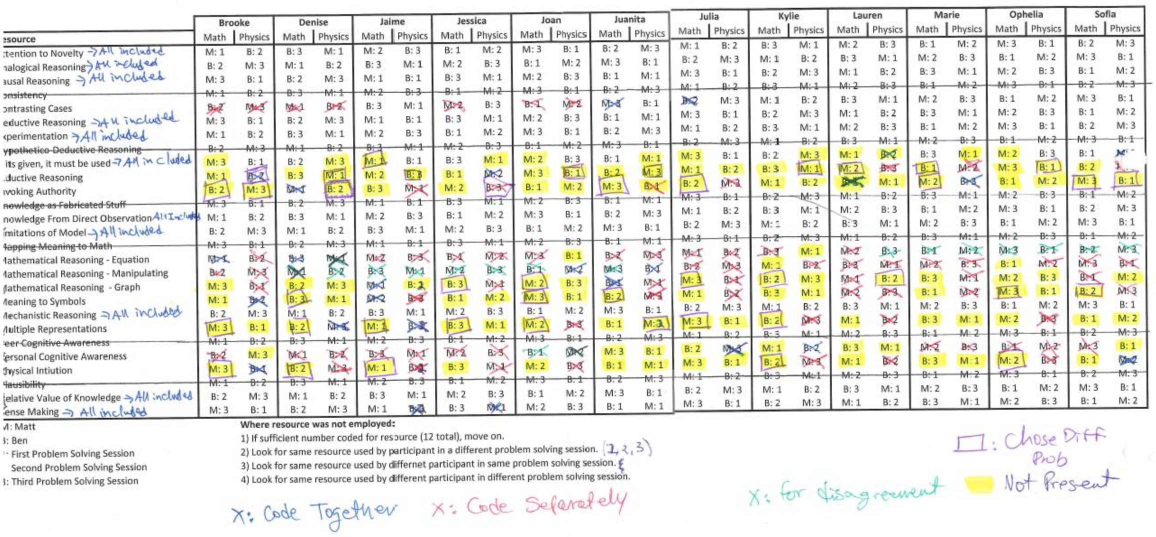
(Both must be met)

II. Example from my Dissertation Study (Denise 1, page 25)

STUDENT: So this would be Negative One and then this Slope right here would be, um Negative One over let's see, eight –no that's nine, over zero the slope rise over run [writing on paper]. [pause] It would be zero. That doesn't make sense [said under her breath]. [staring at paper] [pause] Okay. [exhales] That doesn't help me any.

APPENDIX F—Study 2 Inter-Rater Reliability Documents

Inter-rater reliability instance selection matrix.



esource	Brooke Math	Brooke Physics	Denise Math	Denise Physics	Jaime Math	Jaime Physics	Jessica Math	Jessica Physics	Joan Math	Joan Physics	Juanita Math	Juanita Physics	Julia Math	Julia Physics	Kylie Math	Kylie Physics	Lauren Math	Lauren Physics	Marie Math	Marie Physics	Ophelia Math	Ophelia Physics	Sofia Math	Sofia Physics
ttention to Novelty → All included	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3
nalogical Reasoning → All included	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1
ausal Reasoning → All included	M: 3	B: 1	B: 2	M: 3	M: 1	B: 1	B: 3	M: 1	M: 2	B: 3	B: 1	M: 1	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2
~~onsistency~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~
ontrasting Cases	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1
eductive Reasoning → All included	M: 3	B: 1	B: 2	M: 3	M: 1	B: 1	B: 3	M: 1	M: 2	B: 3	B: 1	M: 1	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2
xperimentation → All included	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3
~~ypothetico-Deductive Reasoning~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~	~~M: 3~~	~~B: 1~~
its given, it must be used → All included	M: 3	B: 1	B: 2	M: 3	M: 1	B: 1	B: 3	M: 1	M: 2	B: 3	B: 1	M: 1	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	[illegible]
ductive Reasoning	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	[illegible]
voking Authority	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1
~~nowledge as Fabricated Stuff~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 1~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 1~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~
nowledge From Direct Observation All Included	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3
imitations of Model → All included	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1
~~apping Meaning to Math~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 1~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 1~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~
athematical Reasoning - Equation	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3
athematical Reasoning - Manipulating	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1
athematical Reasoning - Graph	M: 3	B: 1	B: 2	M: 3	M: 1	B: 1	B: 3	M: 1	M: 2	B: 3	B: 1	M: 1	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2
eaning to Symbols	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3
echanistic Reasoning → All included	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1
ultiple Representations	M: 3	B: 1	B: 2	M: 3	M: 1	B: 1	B: 3	M: 1	M: 2	B: 3	B: 1	M: 1	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2
~~eer Cognitive Awareness~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~
ersonal Cognitive Awareness	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1
hysical Intiution	M: 3	B: 1	B: 2	M: 3	M: 1	B: 1	B: 3	M: 1	M: 2	B: 3	B: 1	M: 1	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2
~~lausibility~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~	~~M: 1~~	~~B: 2~~	~~B: 3~~	~~M: 1~~	~~M: 2~~	~~B: 3~~	~~B: 1~~	~~M: 2~~	~~M: 3~~	~~B: 1~~	~~B: 2~~	~~M: 3~~
elative Value of Knowledge → All included	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2	M: 3	B: 1
ense Making → All included	M: 3	B: 1	B: 2	M: 3	M: 1	B: 1	B: 3	M: 1	M: 2	B: 3	B: 1	M: 1	M: 3	B: 1	B: 2	M: 3	M: 1	B: 2	B: 3	M: 1	M: 2	B: 3	B: 1	M: 2

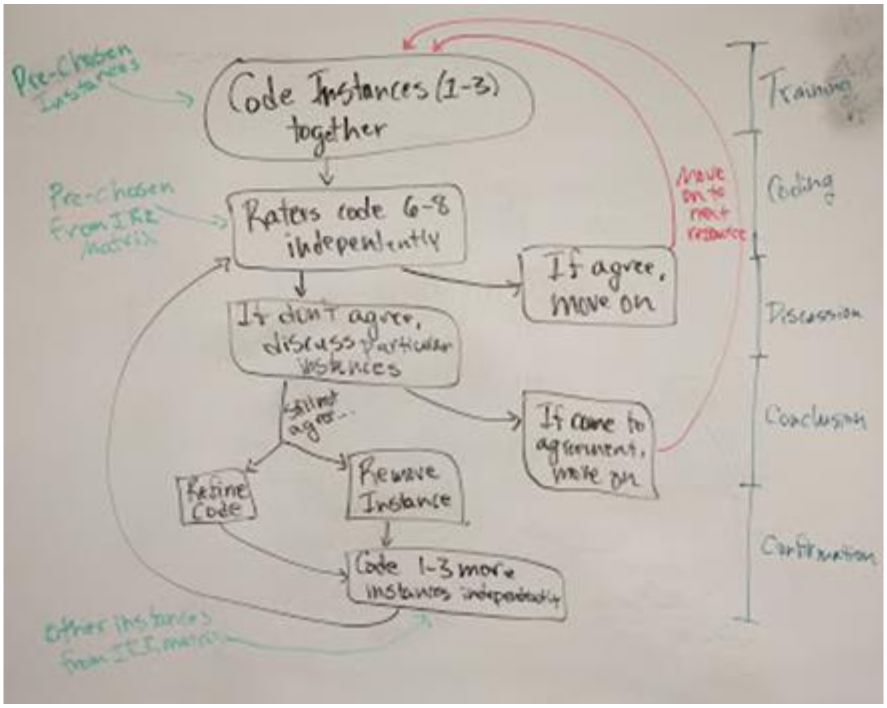
M: Matt
B: Ben
1- First Problem Solving Session
Second Problem Solving Session
3: Third Problem Solving Session

Where resource was not employed:

1) If sufficient number coded for resource (12 total), move on.
2) Look for same resource used by participant in a different problem solving session. (1, 2, 3)
3) Look for same resource used by differnet participant in same problem solving session. ξ
4) Look for same resource used by different participant in different problem solving session.

X: Code Together
X: Code Seperately
X: for disagreement
□: Chose Diff Prob
▬ Not Present

Inter-rater reliability plan.



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