A Grounded Theory Investigation of Thinking and Reasoning with Multiple Representational Systems for Epistemological Change in Introductory Physics

Submitted by

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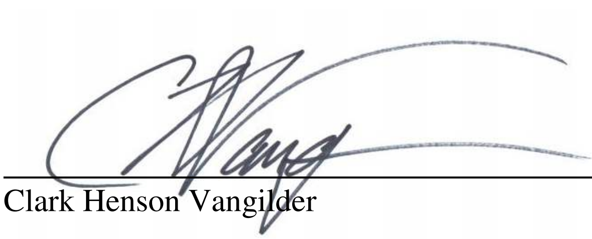

Clark Henson Vangilder	February 8, 2016
	Date

Abstract

Conceptual and epistemological change work in concert under the influence of representational systems, and are employed by introductory physics (IP) students in the thinking and reasoning that they demonstrate in various modelling and problem-solving processes. A grounded theory design was used to qualitatively assess how students used multiple representational systems (MRS) in their own thinking and reasoning along the way to personal epistemological change. This study was framed by the work of Piaget and other cognitive theorists and conducted in a college in Arizona; the sample size was 44. The findings herein suggest that thinking and reasoning are distinct processes that handle concepts and conceptual frameworks in different ways, and thus a new theory for the conceptual framework of thinking and reasoning is proposed. Thinking is defined as the ability to construct a concept, whereas reasoning is the ability to construct a conceptual framework (build a model). A taxonomy of conceptual frameworks encompasses thinking as a construct dependent on building a model, and relies on the interaction of at least four different types of concepts during model construction. Thinking is synonymous with the construction of conceptual frameworks, whereas reasoning is synonymous with the coordination of concepts. A new definition for understanding as the ability to relate conceptual frameworks (models) was also created as an extension of the core elements of thinking and reasoning about the empirically familiar regularizes (laws) that are part of Physics.

Keywords: thinking, reasoning, understanding, concept, conceptual framework, personal epistemology, epistemological change, conceptual change, representational system, introductory physics, model, modeling, physics.

Dedication

This work is dedicated to my marvelous wife, Gia Nina Vangilder. Above all others, she has sacrificed much during the journey to my Ph.D. Her unwavering love and loyalty transcend the practical benefits of her proofreading assistance over the years, as well as other logistical maneuverings pertaining to our family enduring the time commitment that such an endeavor requires of me personally.

You are amazing Gia, and I love you more than mere words can describe!

Most importantly, I thank God Himself for putting my mind in a wonderful universe so rich with things to explore.

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Honorable mention is given Dr. Rob MacDuff, whose influence and collaboration over the years is valuable beyond measure or words. Neither of us would be where we are at without the partnership of theory and practice that has defined our collaboration for more than a decade now. I am truly blessed to know you and work with you.

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Chapter 1: Introduction to the Study

Introduction

The cumulative history of physics education research (PER) for the last 34 years has led to a reform in science teaching that has fundamentally changed the nature of physics instruction in many places around the world (Modeling Instruction Project, 2013; ISLE, 2014). Historical developments in PER have highlighted the connection that exists between conceptual change and the way that students come to learn (Hake, 2007; Hestenes, 2010), the difficulties that impede their learning (Lising & Elby, 2005), the connection between personal epistemology and learning physics (Brewe, Traxler, de la Garza & Kramer, 2013; Ding, 2014; Zhang & Ding, 2013), and theoretical developments that inform pedagogical reform (Hake, 1998; Hestenes, 2010). To date, little research has been done exploring the particular mechanisms of general epistemological change (Bendixen, 2012), with PER pioneers such as Redish (2013) suggesting the need for a basis in psychological theory for how physics students think and believe when it comes to learning and knowledge acquisition. There is still no definitive answer about general epistemological change within the literature (Hofer, 2012; Hofer & Sinatra, 2010), and many of the leading researchers have been studying that with the context of mathematics and/or physics (see Hammer & Elby, 2012; Schommer-Aikins & Duell, 2013).

The central goal of this research was to determine how students encode meaning through the deployment of multiple representational systems (MRS)—such as words, symbols, diagrams, and graphs—in an effort towards thinking and reasoning their way through epistemological change in an Introductory Physics (IP) classroom. Specifically, this study positions MRS as tools for thinking and reasoning that are capable of producing epistemological change. Among other things, the study sought to find the types and numbers of MRS that are the most useful in producing epistemological change. Such findings would then inform the PER community concerning the capacity that MRS have for encoding meaning during the scientific thinking and reasoning process. Moreover, the relative importance of personal epistemology in the process of conceptual change—either as a barrier or a promoter—is the kind of information needed for continued progress in the PER reform effort, as well as learning theory in general. The PER Community has a number of peer-reviewed journals such as the American Journal of Physics (see Hake 1998, 2007; Lising & Elby, 2005; Redish 2013) and the Physical Review Special Topics - Physics Education Research (see Bing & Redish, 2012; Bodin, 2012; Brewe, 2011; De Cock, 2012; Ding, 2014), where much of the research is reported.

The multi-decade findings of both the PER community and the researchers involved with personal epistemology, indicate a deep connection between learning physics and beliefs about the world, as well as how those epistemic views correspond to conceptual change. It is impossible to do Physics without the aid of conventional representational systems such as natural language and mathematics; hence the inherent capacity for those representational systems to influence both conceptual and epistemic knowledge (Plotnitsky, 2012) is a legitimate point of inquiry that has gone largely unnoticed. The usage of one or more representational systems should inform researchers of what the students is thinking or reasoning about—specifically, the ontology, and therefore the beliefs that such a learner has concerning what has been encoded by MRS. Beliefs about reality and the correspondence to Physics are inextricably linked through MRS.

According to Pintrich (2012), it is unclear at this time how representational systems influence epistemological change when deployed in learning environments of any type. Historically, the lessons learned from the advance of the learning sciences have shown that personal choices in representational systems are critical to the metacognitive strategies that lead to increased learning and knowledge transfer (Kafai, 2007) when situated in learning environments that are collaborative and individually reflective against the backdrop of prior knowledge (Bransford, Brown, Cocking, & National Research Council, 1999). The central goal of this research was to determine how thinking and reasoning with multiple representational systems (MRS)—such as diagrams, symbols, and natural language—influences epistemological change within the setting of an IP classroom. The study described herein positions adult community college students in a learning environment rich with conceptual and representational tools, along with a set of challenges to their prior knowledge and beliefs. This study answers a long-standing deficit in the literature on epistemological change (Bendixen, 2012; Pintrich, 2012) by providing a deeper understanding of the processes and mechanisms of epistemological change as they pertain to context (domain of knowledge) and representational systems in terms of the psychological constructs of thinking and reasoning. This chapter will setup the background for the study research questions based on the current and historical findings within the fields of personal epistemology research, and the multi-decade findings of the PER community.

Background of the Study

The current state of research on personal epistemology is one of theoretical competition (Hofer, 2012: Pintrich, 2012), concerning how learners situated within different contexts, domains of inquiry, and developmental stages obtain epistemological advancement, as well as whether or not to include the nature of learning alongside the nature of knowledge and knowing in the definition of personal epistemology (Hammer & Elby, 2012). The term epistemology deals with the origin, nature, and usage of knowledge (Hofer, 2012), and thus epistemological change addresses how individual beliefs are adjusted and for what reasons. Moreover, the field has not produced a clear understanding of how those learners develop conceptual knowledge about the world with respect to their personal beliefs about the world (Hofer, 2012). Conceptual change research has not faired much better, and suffers from a punctuated view of conceptual change that has been dominated by pre-post testing strategies rather than process studies (diSessa, 2010). According to Hofer (2012), future research needs to find relations between psychological constructs and epistemological frameworks in order to improve methodology and terminology such that comparable studies can be conducted—thus unifying the construct of personal epistemology within the fields of education and developmental psychology. Bendixen (2012) suggested that little research on the processes and mechanisms of epistemological change have been done, and echo the call by Hofer and Pintrich (1997) for more qualitative studies examining the contextual factors that can constrain or facilitate the process of personal epistemological theory change. Moore (2012) cited the need for research addressing the debate over domain-general versus domain-specific epistemic cognition in terms of the features of learning environments that influence learning and produce qualitative changes in the complexity of student thinking.

Wiser and Smith (2010) described some of the deep connections that exist between concept formation, ontology, and personal epistemology, within a framework of metacognitive control that is central to modeling phenomena through both top-down and bottom-up mental processes. These sorts of cognitive developments depend on the ability to use representational systems that are rational (mathematics) and/or metaphorical (natural language), within a methodological context that is empirical (measurement) in nature. The student's transition from holding a naïve theory—such as objects possess a force property—to holding a more sophisticated or expert theory—that forces act on objects (Hammer & Elby, 2012)—is by means of representational systems that serve in part as epistemic resources for modeling real-world phenomena (Bing & Redish, 2012; Moore et al., 2013). Moreover, it is the coupling of internal representations (mental models) with the external representations that we call models, which is critical to the reasoning process (Nersessian, 2010) and its assessment. These findings suggest an intimate connection between personal epistemology and representational systems as they function in concert with thinking, reasoning, and conceptual change; however, they do so without specifying any particular tools. The central aim of this research is to describe how MRS are used in the thinking and reasoning that accompanies epistemological change.

Personal epistemology. Personal Epistemology (PE) has been an expanding field of inquiry for at least 40 years, with a coalescence of a handful of models and theories emerging in the late 1990s to early 2000s—such as process and developmental models, and at least four different assessment instruments for judging the epistemic state of learners at most any age (Herrón, 2010; Hofer & Pintrich, 2012). While the current models and theories agree on the relationships to variables such as gender, prior knowledge, beliefs about learning, and critical thinking (Herrón, 2010), it is not clear at this time whether or not a unitary construct for personal epistemology applies in all cases—suggesting a number of domain-specific (knowledge area such as science) gaps that need further research.

The content of physics is neither purely rational nor empirical, but also depends on metaphorical representations—such as the term *flow* for energy transfer, light is a *particle/wave*, and electrons *tunneling* through quantum spaces—in order to foster the understanding of complex phenomena and their underlying theories (Brewe, 2011; Lancor, 2012; Scherr, Close, McKagan, & Vokos, 2012; Scherr, Close, Close, & Vokos, 2012). One of the earliest attempts to measure personal epistemology was the Psycho-epistemological Profile (PEP) (Royce & Mos, 1980), which measures personal epistemology on three dimensions: Rational, Empirical, and Metaphorical, and is therefore an ideal assessment tool for scientific domains of epistemology. The rational dimension of PEP assumes that knowledge is obtained through reason and logic, whereas the empirical dimension derives and justifies knowledge through direct observation. The metaphorical dimension of PEP *defines* knowledge as derived intuitively with a view to subsequent verification of its universality.

Representational Systems. Schemata theory (Anderson et al., 1977) suggested a dynamic process of memory storage and retrieval in concert with the use of representational systems lead to schemata, which serve as interpretive frameworks within the process of epistemological advancement. Under the Modeling Instruction Theory for Teaching Physics (Hestenes, 2010) students are taught to use a representational tool known as a system schema that represents an abstraction of a given picture of some physical situation. Specifically, this diagrammatic tool compels students to represent various objects and interactions with regard to the system that governs them, and these relationships are then productive for various aspects of the problem-solving event. One of its capacities is as an error-checking device that validates (or invalidates) the equation model of the same system—such as verifying the equation set adequately represents the superposition of forces. Simply put, you can move forward with a solution (decision) once you have verified that nothing was (a) left out of the model or (b) included illegitimately. The use of multiple representational systems within an IE classroom force the reconciliation of multiple schemata on singular and/or connected phenomena. This sort of conceptual turbulence challenges the epistemic stance of the learner, and thereby provides an opportunity to detect epistemological change as a function of MRS.

Hestenes (2010) deployed multiple types of representations for encoding structure in terms of systemic (links among interacting parts), geometric (configurations and locations), object (intrinsic properties), interaction (causal), and temporal (changes in the system) as ways to model and categorize the observation that students of science make in an effort to mimic the expert view. In these ways, MRS are instrumental for the modeling the structure of physical phenomena (Plotnitsky, 2012; Scherr et al., 2012), and therefore serve as evidence of what students believe the varied representational conventions of mathematics and physics are capable of describing. The status as of MRS as elements of epistemological change is the primary research question in this study.

Problem Statement

It was not known how (a) thinking and reasoning with MRS occurs, and (b) how that sort of thinking and reasoning affects epistemological change in terms of mechanisms and processes—whether cognitive, behavioral, or social—in an IP classroom. Moreover, as shown in the review of the literature herein, it is not clear what *anyone* means by the terms thinking and reasoning within any context. The use of representational systems—such as symbols, diagrams, and narratives—is undoubtedly central to the progress of science education by virtue of its ubiquitous deployment in the realm of natural science itself (Plotnitsky, 2012; Scherr, Close, McKagan & Vokos, 2012). Given the *cognitive filter* that personal epistemology provides for the acquisition and the application of knowledge (Schommer-Aikins, 2012), it seemed reasonable to investigate the nature of epistemological change in concert with the thinking and reasoning that occurs by means of the representational systems associated with a domain of knowledge—such as IP. The importance of this study hinged on its ability to answer a long-standing deficit in the literature on epistemological change (Bendixen, 2012; Pintrich, 2012) by providing a deeper understanding of the processes and mechanisms of epistemological change as they pertain to context (domain of knowledge) and representational systems in terms of the psychological constructs of thinking and reasoning. These findings better inform the Physics Education Research (PER) community concerning the capacity that MRS have for encoding meaning during the scientific thinking and reasoning process, while simultaneously clarifying what is meant by those processes. Moreover, the relative importance of personal epistemology in the process of conceptual change—either as a barrier or a promoter—is the kind of information needed for continued progress in the PER reform effort, as well as learning theory in general. The importance of advancing scientific thinking and reasoning, conceptual change—in terms of epistemological change—lies in the clear evidence from PER that conceptual change has a positive effect on achievement in terms of problem-solving skills (Coletta & Phillips, 2010; Coletta, Phillips & Steinert, 2007a; Hake, 2007).

Purpose of the Study

The purpose of this qualitative grounded theory study was to determine how representational systems deployed in an IP classroom correspond to epistemological change in accordance with the ways that students therein think and reason, within a study sample at Central Arizona College—located in Coolidge, Arizona. The collaborative and writing-intensive nature of the IP curriculum at Central Arizona College lends itself well to the research questions and methodology of this study. The use of representational systems—such as symbols, diagrams, and natural language—is undoubtedly central to the progress of science education by virtue of its ubiquitous deployment in the realm of natural science itself (Plotnitsky, 2012; Scherr, Close, McKagan & Vokos, 2012). Given the *cognitive filter* that personal epistemology provides for the acquisition and the application of knowledge (Schommer-Aikins, 2012), it seemed reasonable to investigate the nature of epistemological change in concert with the thinking and reasoning that occurs by means of the representational systems associated with a domain of knowledge—such as IP. The researcher identified the mechanisms of epistemological change (Bendixen, 2012) as they correspond to thinking and reasoning with MRS. The value of such knowledge to educational reform efforts is significant in terms of (a) the specific mechanisms for epistemological change (Bendixen, 2012), and (b) the psychological constructs that generate them (Hofer, 2012).

Ongoing PER reform efforts—such as the development of assessment instruments and pedagogical change—will benefit tremendously from knowing the types and frequencies of deployment for representational systems that are effective for producing conceptual and epistemological change in IP. Furthermore, the relative frequency of use coupled with personal stances about the usefulness of those representational systems will provide the information needed to reform instruction in topics that tend to confuse students during their learning trajectory.

Research Questions and Phenomenon

The goal of this qualitative grounded theory study was to determine the influence that multiple representational systems (MRS) have on the thinking and reasoning of 20-30 community college IP students at Central Arizona College with respect to their conceptual frameworks and personal epistemology. Forty-four semi-structured interviews based on instructional goals, survey response data, and student journal entries were conducted at regular intervals during the study in order to obtain emergent themes concerning how students think and reason about symbols and operations in mathematics, as well as how they monitor their own thinking about the same. Journals and semi-structured interviews—in the form of group Socratic dialogs—reveal the ways in which students shift between representational systems (*languages*) in an effort to model mathematical systems, while providing ample means for triangulating the data in parallel with field notes and memos made by the author-researcher. Multiple electronic polls were given throughout the treatment in order to capture opinions about thinking and reasoning, knowledge acquisition and usage, as well as how concepts and beliefs change as a result.

As shown in the forthcoming review of the literature, thinking and reasoning are poorly defined and often conflated (Evans, 2012; Evans & Over, 2013; Mulnix, 2012; Nimon, 2013; Peters, 2007). Given the absence of consensus on the definitions of thinking and reasoning within the research literature, the author proposed new definitions for thinking and reasoning as a means for coding, counting, and classifying instances of student thinking and reasoning with representational systems that were based on the synthesis of a model for thinking put forward by Paul and Elder (2008). Thinking is defined as the ability to construct a model, and reasoning is defined as the ability to relate two or more models. A model is simply any representation of structure, and structure refers to the way in which relations can be encoded (Hestenes, 2010). The following research questions were crafted in such a manner as to encompass the gap in the literature related to the process and mechanisms of epistemological change as they relate to the psychological constructs of thinking and reasoning within the domain of IP, as well as the features of Hofer's epistemic cognition model (Hofer, 2004; Sinatra, Kienhues, & Hofer, 2014) involving the domain of knowledge, the contextual factors of the learning environment, and how student reflection within the curriculum conveys towards metacognitive monitoring.

Qualitative Research Questions

R_1: How do IP students use representational systems in their thinking and reasoning?

R_2: How does the use of MRS in the thinking and reasoning of IP students promote personal epistemological change?

In order to facilitate an investigation of these research questions, a series of activities comprising the standard curriculum of IP students at a rural community college will be studies. Beginning with group discussions, journals and surveys on the nature of Physics and reality, students then begin to deploy new representational systems designed to expose and refine conceptions of number and mathematical operations that are critical to the language of Physics. These advances are then carried forward to an investigation of motion that serves as the basis of the entire course. Exit interviews at the semesters end reflected on all that was learned and how the conceptual and representational tools used throughout the course influence thinking, reasoning, and personal epistemology.

Advancing Scientific Knowledge

As described in the forthcoming literature review, a lack of clarity exists in the literature concerning the definitions of thinking and reasoning; however, there is an abundance of claims that all sorts of thinking and reasoning underlie every advance in human learning. In order to facilitate more efficient data collection, the author introduced definitions of thinking and reasoning as follows. Thinking is defined as the ability to construct a model. This definition is (a) flexible enough to encompass any representational system, (b) straightforward enough to permit the kinds of frequency distributions and classification schemes that enable direct measurement of this cognitive behavior, and is (c) inspired by the work of PER pioneers cited herein, such as Hestenes, Hake, Redish, and Mazur. The term *model* is simply any representation of *structure* (Hestenes, 2010), and structure is a broader term—open to wide interpretation—

encompassing the way that interconnectedness between and within systems is articulated. Furthermore, the term reasoning is defined herein as the ability to relate two or more models; and therefore, coordinates the terms in a manner that lends consistency and coherence to the measure of these cognitive behaviors by simply counting attempts.

Little research has been done exploring the particular mechanisms of epistemological change along developmental trajectories or with respect to the dimensions of personal epistemology (Bendixen, 2012; Hofer, 2012). Moreover, it was not known how representational systems influence such change when deployed in learning environments of any type (Pintrich, 2012). Personal epistemology is linked to conceptual change (Bendixen, 2012; Hofer, 2012), and representational systems are required for producing conceptual change (diSessa, 2010). The gap in the literature that this study addresses is the lack of connections that exists between representational systems, conceptual change, and epistemological change, and what processes and mechanisms are productive for such change (Bendixen, 2012; Hofer, 2012; Pintrich, 2012). The persistent question of educational research is ‘what works best and why?’ and it is the *lived* experience of learners situated in an IP classroom that should expose their thoughts and beliefs concerning the representational tools that they use and/or struggle with when encoding for meaning.

The PER literature speaks extensively to improving the thinking and/or reasoning skills of students in introductory physics courses (Coletta & Phillips, 2010; Coletta et al., 2007a; Hake, 2007), without ever providing or relying on a clear definition for thinking or reasoning in general terms. Thinking and reasoning within the context of problem solving is part of the functional relationship that exists between the personal epistemology of students and their learning in general (Lising & Elby, 2005; Schommer-Aikins & Duell, 2013). The use of representational systems—such as symbols, graphs, diagrams, and narratives—is undoubtedly central to the progress of science education by virtue of its ubiquitous deployment in the realm of natural science itself. The evidence cited herein shows a lack of clarity on the mechanisms of conceptual and epistemological change as they correspond to (1) one another, and (2) towards problem-solving skills. Moreover, it is not clear what sort of thinking and reasoning is being deployed in an effort to produce those changes in a knowledge-domain requiring MRS (Plotnitsky, 2012). This study addressed all of these concerns at the focal point of epistemological change, and thus answered the call for clarity and mechanistic description within the literature.

Significance of the Study

The role of representational systems is believed to be a factor in promoting conceptual and epistemological change in settings such as Introductory Physics classrooms (Brewe et al., 2013), as well as learning in general (Lising & Elby, 2005; Pintrich, 2012). This research sought to understand (1) what, if any, connection(s) exist between thinking and reasoning with MRS and epistemological change—as prescribed in the research questions, and then (2) begin to *unravel* the types and numbers of representational systems that are effective for promoting those changes by specifying the mechanisms (Bendixen, 2012) and processes (Hofer, 2012) found therein. The value of such knowledge to educational reform efforts is significant, as it identified specific mechanisms for epistemological change (Bendixen, 2012) in terms of the psychological constructs that generate them (Hofer, 2012), as well as the epistemic resources for conceptual formation (Bing & Redish, 2012; Wiser & Smith, 2010) and change (Jonassen, Strobel, & Gottdenker, 2005) within learning environments designed for epistemic change (Muis & Duffy, 2013).

The importance of epistemological change for this study is evident in its close connection to the field of conceptual change (diSessa, 2010) and how they are coordinated in PER through the use of representational systems (Brewe et al., 2013). Moreover, epistemological change would be better understood in terms of the influence of representational systems (Pintrich, 2012) and the incremental processes associated with conceptual change (diSessa, 2010), while also contributing to the lack of theoretical clarity that persists in defining each of these constructs (Hofer, 2012; Pintrich, 2012). A secondary goal that is inextricably linked to the primary goal, is to clearly distinguish thinking and reasoning from one another, and how MRS are used to encode the meaning evident in those constructs. Such a discovery has the potential for providing a general metric for the constructs of thinking and reasoning in any domain of knowledge with respect to the representational systems that accompany it.

Personal epistemology has connections with multiple *fields* of psychology and learning science including conceptual change (diSessa, 2010; Jonassen et al., 2005, Nersessian, 2010), metacognition (Barzilai & Zohar, 2014; Bromme, Pieschl, & Stahl, 2010; Hofer, 2012; Hofer & Sinatra, 2010; Mason & Bromme, 2010; Muis, Kendeou & Franco, 2011), self-regulated learning (Cassidy, 2011; Greene, Muis & Pieschl, 2010; Muis & Franco, 2010), and self-efficacy through locus of control (Cifarelli, Goodson-Espy, & Jeong-Lim, 2010; Kennedy, 2010). Each of these constructs or cognitive functions are communicated through representational systems that students presumably think and reason about along their way to an understanding that shapes their set of personal beliefs. Research that seeks to obtain a deeper understanding of the processes and mechanisms associated with changes along any of those dimensions will have a lasting impact on multiple areas of psychology and learning science in general.

The PER community has promoted, created, and uncovered a vast array of IE methods that have surely improved learning outcomes in IP classrooms (Coletta & Phillips, 2010; Coletta et al., 2007a; Hake, 1998; Hestenes, 2010)—and therefore some sort of cognitive behavior. So while there is little doubt that some sort of thinking and/or reasoning is going on while students are learning any topic, it is not clear in the literature what the specific qualities of thinking and reasoning are when it comes to learning in IP. Given the deep connections that exist between metacognition and epistemological frameworks (Barzilai & Zohar, 2014), the effort to obtain the factors of epistemological change in terms of the tools that are instrumental to that effect present a grand opportunity to the teaching and learning enterprise.

Rationale for Methodology

A qualitative approach was used in this study. The foundations of qualitative research rest on the inductive analysis that makes developing an understanding of the phenomena from the viewpoint of the participants possible (Merriam, 2010) in a manner that respects how the meaning is constructed in social settings (Yin, 2011) where the researcher is the primary data collection *instrument* responsible for producing a richly descriptive account of the outcomes (Merriam, 2010). Given the nature of the study on personal epistemology—beliefs about knowledge and its acquisition—and how students obtain advances in personal epistemology, qualitative methods lend themselves best to the project described herein because they provide a richer description (Schommer-Aikins, 2012), of the lived experience of the study participants (Charmaz, 2006; Glaser & Strauss, 2009). Moreover, given that the research design was grounded theory, the necessity of qualitative methodology for data collection and analysis is properly constrained within this methodology by virtue of its underlying logic and interpretive framework (Charmaz, 2006).

Nature of the Research Design for the Study

A grounded theory approach (Charmaz, 2006) was used in designing this qualitative study in order to produce a substantive theory capable of describing the complex interactions that comprise the phenomena of thinking and reasoning with MRS, and its influence on epistemological change within the context of a community college IP classroom. Grounded theory is a qualitative design that allows a researcher to form an abstract theory of processes or interactions that are *grounded* in the views of the participants (Charmaz, 2006; Glaser & Strauss, 2009). Given the fact that personal epistemology is entirely about personal beliefs and viewpoints, a grounded theory exploration of the underlying mechanisms and processes of epistemological change is entirely consistent with the research questions probing *how* students think and reason their way towards epistemological change using MRS.

Approximately 30 students comprise the study population from which archived data will be drawn at Central Arizona College—which is consistent with the 20-30 study participants recommended for grounded theory research by Creswell (2013), and the 30-50 participants suggested by Morse (2000). Charmaz (2006) suggested that 25 interviews are sufficient for grounded theory designs on small projects. Given the current study is using interviews, written journals, and electronic polls, a group of slightly more than 30 student participants should be more than adequate for obtaining the level of theoretical saturation which is the ultimate criterion for sample size in grounded theory designs (Corbin & Strauss, 2008). The archived data in this study will include numerous student journals throughout the IP curriculum, group discussion transcripts, and miscellaneous assessment results—such as Force Concept Inventory (FCI), and the Psycho-epistemological Profile (PEP)—that are all part of the normal classroom experience of IP students at Central Arizona College, which were selected purposively due to their suitability for the study and amount of data available for the researcher. In order to eliminate as much researcher bias as possible, archived data was used.

Grounded theory design was selected because of its capacity to capture in theory the 'how' of structure and process within a social setting, versus a phenomenological 'what' of the events (Birks & Mills, 2011). The research questions proposed for this study ask how MRS are used in the processes of thinking and reasoning within epistemological change, and thus fall under the heading of grounded theory by virtue of the research question itself—which seeks an answer to a how type of question. In order to make the connection to epistemological change in these terms though, a certain amount of discourse analysis is required. However, discourse analysis alone cannot answer the 'how' questions because such a design is methodologically constrained to the meaning that is negotiated in the 'what' of language rather than the process of negotiating meaning with language itself (Yin, 2011). Though phenomenology, discourse analysis, and grounded theory come from different historical and philosophical traditions, the boundaries between them are somewhat porous in terms of the methodology required for a particular kind of research question (Yin, 2011), as well as the fact that the elements of one type of question—such as a ‘how’ question—often entail elements of another type of research question, such as the ‘what’ type (Starks & Trinidad, 2007).

Since the nature of this study’s research questions probe how students use MRS in their thinking and reasoning for epistemological change, the importance of using grounded theory as a tool for *grounding* the theory in the particular viewpoints of the participants (Charmaz, 2006; Glaser & Strauss, 2009) further solidifies the primacy of grounded theory over other designs—such as discourse analysis. Personal epistemology obviously pertains to personal viewpoints, which must be expressed in language. The language used by IP students is situated in social contexts constrained by the MRS that are conventionally used within Physics—such as graphs, equation, pictures, and words (Plotnitsky, 2012). In this case, the viewpoints that are the central focus of personal epistemological change are developing within a context that can only be described using a limited set of representational systems. The connection between the personal and social aspects of the learning environment for this study, in parallel with the particular uses of MRS (language), was far too intimate to ignore.

Definition of Terms

Conceptual change. In order to define conceptual change, one must first define a concept. In general, it is the internal representation that learners construct for themselves based on the external representations of others (Nersessian, 2010). Conceptual change is measured on many levels from the taxonomic and semantic aspects of how symbols are related to referents, as well as how those representations correspond to more complex conceptual structures such as an event (Hestenes, 2010).

Multiple representational systems (MRS). The use of words, symbols, and pictures to in order to communicate an idea or present a model is described as multiple representations (Fyfe, McNeil, Son, & Goldstone, 2014; Harr et al., 2014), multiple external representations (Fyfe et al, 2014; Wu & Puntambekar, 2012), and multiple representational systems (Ainsworth, Bibby, & Wood, 2002) in the literature.

Personal epistemology. The psychological construct of personal epistemology is used to describe how personal beliefs convey to what knowledge is, how it is obtained, what it is used for, and how useful it is in any context (Hofer & Pintrich, 2012).

Assumptions, Limitations, Delimitations

The following assumptions are given with respect to this study.

1. It was assumed that survey participants in this study were not be deceptive with their answers, and that the participants answered questions honestly and to the best of their ability. The course and curriculum under study was the regular curriculum for Physics students at Central Arizona College, and therefore part of the normal experience that counts for a grade.

2. It is assumed that this study was an accurate representation of what is typical in IE IP classrooms. The instructor (the author) has been trained in IE methods for the last decade and has based his research on the best practices of the PER community.

The following limitations/delimitations apply to this study. The generalizability of the findings that emerge from this study are limited to the IE class of IP classrooms typically studied by the PER community. According to Merriam (2010), generalizability in qualitative research must be thought of differently than it is in quantitative designs. External validity is the qualitative equivalent of generalizability, and is constrained by the perception that users of the research have with regard to the transferability to another context or domain of knowledge. The author makes no claims with regard to generalizability in this study aside from the likelihood that this design could produce similar results in other IE IP classrooms. This limitation is consistent with the theoretical and pedagogical norms that persist in that category of instructional practice. One long-term goal of this dissertation is preparatory towards the development of a learning theory requiring a great deal more than is typically contained in just one dissertation.

1. The student body was not randomly selected. This qualitative study depends on purposive sampling of qualified students, which was obtained by identifying students who meet the pre-requisites for taking physics for university transfer purposes.

2. The study population was limited to two Physics courses at one community college. The author-researcher has no other access to students.

Summary and Organization of the Remainder of the Study

Conceptual change and epistemological change are connected by the representational systems used by learners when deploying them in contexts that require modeling (Hestenes, 2010, Nersessian, 2010). Learning physics requires thinking and reasoning within a context for problem solving where beliefs about the world are regularly challenged (Lising & Elby, 2005). However, there is no clear definition of the terms thinking and reasoning (Nimon, 2013; Peters, 2007) even though scores of types of thinking are well attested within the literature—specifically with respect to this study: scientific thinking and reasoning within the context of learning physics (Coletta et al., 2007a, 2007b; Hake, 1998; Hestenes, 2010).

Chapter 2 presents a review of current and historical research on the connections that exist between thinking, reasoning, representational systems, conceptual change and epistemological change, as well as the theoretical foundations underlying the present study. Chapter 3 describes the methodology and research design for a generic qualitative design, and the data collection and analysis procedures for this investigation. Chapter 4 delivers the actual data analysis with written and graphic summaries of the results, which lead into an interpretation and discussion of the results, as they relate to the existing body of research related to the dissertation topic.

The timeline for completing this dissertation consists of three primary stages. In stage one, the proposal is completed and approved by August 13, 2014—the end of PSY955 Dissertation 1, and subsequently approved in PSY960 Dissertation 2. Data collection begins immediately in PSY960 Dissertation 2 in conjunction with the start of the courses being studied at Central Arizona College that begin on August 18th. The analysis phase began subsequent to the approved Proposal in July 2015, and the data analysis was completed during PSY969 Research Continuation 4. The remainder of the dissertation was completed during PSY970 Research Continuation 5 in January 2016.

Chapter 2: Literature Review

Introduction to the Chapter and Background to the Problem

The basic premise of this research was that the use of MRS is the fundamental feature of the kinds of thinking and reasoning that promote both conceptual and epistemological change; however, this study was concerned with just the connections that exist between thinking and reasoning with MRS and personal epistemological change. Specifically, that the resources for conceptual change are contingent on the resources for epistemic change, if not entirely the same. Moreover, the inherent need of representational systems for communicating meaning is central to conceptual change as well as the set of personal beliefs that accompany personal epistemology. The extent to which epistemological change is connected to the deployment of MRS, is the central research focus that is capable of better informing all PER initiatives concerning the foundations of thinking and reasoning required for this sort of change.

The current state of research on the personal epistemology of learners situated within different contexts, domains of inquiry, and developmental stages, has not produced a clear understanding of how those learners (a) develop conceptual knowledge about the world with respect to (b) their personal beliefs about the world as it (c) relates to physics (Hofer, 2012). However, there is evidence showing that when the science pedagogy matches the science practice, then students are more likely to obtain positive conceptual change based on the features of instruction and curricular content upon which student beliefs about the world are formed (Lee & Chin-Chung, 2012). Conceptual change research has also failed to produce clear understanding of how learners develop conceptual knowledge about the world, and suffers from a punctuated view of conceptual change that has been dominated by pre-post testing strategies rather than process studies (diSessa, 2010).

According to Hofer (2012), future research needs to find relations between psychological constructs and epistemological frameworks. Bendixen (2012) suggested that little research on the processes and mechanisms of epistemological change have been done, and echo the call by Hofer and Pintrich (1997) for more qualitative studies examining the contextual factors that can constrain or facilitate the process of personal epistemological theory change. The general call for studies probing the connections that exist between conceptual and epistemological change, as well as the processes and mechanisms that are productive for those changes, is clearly warranted by these findings. Moreover, the PER literature also includes studies into the connection between personal epistemology and conceptual change in terms of representational systems (Brewe et al., 2013; Lising & Elby, 2005), lending further warrant to the study proposed herein. Though the particular research questions for this study were focused on epistemological change, the findings cited thus far warrant a discussion of conceptual change in this literature review.

Wiser and Smith (2010) describe some of the deep connections that exist between concept formation, ontology, and personal epistemology, within a framework of metacognitive control that is central to modeling phenomena through both top-down (perceptions influenced by prior knowledge) and bottom-up (perceptions influenced by new data) mental processes. These sorts of cognitive developments depend on the ability to use representational systems that are rational (mathematics) and/or metaphorical (natural language), within a methodological context that is empirical (measurement) in nature. The student's transition from naïve to expert theories is by means of representational systems that serve in part as epistemic resources for modeling real-world phenomena (Bing & Redish, 2012; Hestenes, 2010; Moore et al., 2013). Moreover, it is the coupling of internal representations (mental models) with the external representations that we call models, which is critical to the reasoning process and its assessment (Nersessian, 2010). These findings suggest an intimate connection between personal epistemology and representational systems as they function in concert with thinking, reasoning, and conceptual change; however, they do so without specifying any particular tools. The central aim of this research was to identify some of the most basic representational tools that are instrumental for epistemological change.

The Physics Education Research (PER) community has claimed significant gains in student thinking and reasoning (Coletta & Phillips, 2010; Coletta et al., 2007a; Hake, 2007) through conceptual change (Hake, 1998), without ever defining what is meant by the terms thinking and reasoning. As shown in the forthcoming review of the literature, thinking and reasoning are poorly defined and often conflated (Mulnix, 2012; Nimon, 2013; Peters, 2007). In order to facilitate more efficient data collection, the author introduced definitions of thinking and reasoning as follows. Thinking is defined as the ability to construct a model. This definition is (1) flexible enough to encompass any representational system, (2) straightforward enough to permit the kinds of frequency distributions and classification schemes that enable direct measurement of this cognitive behavior, and is (3) inspired by the work of PER pioneers cited herein, such as Hestenes, Hake, Redish, and Mazur. The term *model* is simply any representation of *structure* (Hestenes, 2010), and structure is a broader term—open to wide interpretation—

encompassing the way that interconnectedness between and within systems is articulated. Furthermore, the term reasoning is defined herein as the ability to relate two or more models; and therefore, coordinates the terms in a manner that lends consistency and coherence to the measure of these cognitive behaviors by simply counting attempts.

Though the reform movement as studied in the PER literature has obtained notable success (Coletta et al., 2007a, 2007b; Hake, 1998), one question that emerges from the gaps in this body of literature, as well as the persistent conflation of the terms thinking and reasoning that are common to both the literature and the discourse of math and science education research (Glevey, 2006), is what exactly do we mean by thinking and reasoning?

The search terms “definition of thinking” OR “thinking is defined” in scholarly journals whose names include psycholog* OR cogn* OR educ* yielded only 118 peer-reviewed articles from 1963 to 2014 in EBSCO Academic Search Complete (EBSCO), and 47 articles from 1991 – 2014 in ProQuest—as illustrated below in Table 1.

Table 1

Literature Review Search Pattern 1

Date Range	Type of thinking	Hits in EBSCO	Hits in ProQuest
1963 - 2014	Critical	27	—
	Other	91	—
1991 - 2014	Critical	—	23
	Other	—	24

These initial search results indicate dominance on the field of research by critical thinking that has remained stable over the years since 1963, yet waning in recent years. In both databases, the table entry for “other” is predominantly filled with n = 1 tallies, while the remainder are n = 2. In other words, somewhere between one-half and three-quarters of published research on thinking is scattered among scores of types of thinking distinct from critical thinking, or types of thinking such as schizophrenic thinking, that are not applicable to this study. Table 2 below illustrates a more recent tally for the search terms given above.

Table 2

Literature Review Search Pattern 2

Date Range	Type of thinking	Hits in EBSCO	Hits in ProQuest
2004 - 2014	Critical	16	5
	Other	70	15
2009 - 2014	Critical	8	3
	Other	31	8

Applying the same search criteria for a definition of reasoning yielded only 31 articles in EBSCO for the years 1981 – 2014, and 6 articles in ProQuest for the years 1996 – 2014. Restricting the years to 2004 – 2014 produced on 4 ProQuest and 21 EBSCO articles, whereas a 2009 – 2014 search obtained only 3 ProQuest and 9 EBSCO articles. Changing the search constraints in both databases to just the term “thinking” produced 946 EBSCO and 652 ProQuest articles for the years 2004 – 2014. This means that at best, roughly 9% of all research making claims about thinking in the last 10 years operated with a clear definition of the term. An identical search for the term “reasoning” produced 601 EBSCO and 152 ProQuest articles—indicating that approximately 3% of research articles in the last 10 years made claims about reasoning without the aid of a basic definition.

This review of the literature was structured in terms of how the theories and the histories of conceptual and epistemological change correspond to the progress of learning in general, and physics in particular. Though the study was particularly focused on epistemological change, thinking and reasoning within the context of IP has been historically concerned with conceptual change. However, a great deal of research in personal epistemology has occurred within IP classrooms; hence the need to give attention to both conceptual and epistemological change in this literature review. Additionally, the constructs of thinking and reasoning were considered in general psychological terms as well as the particulars of Physics education. Self-regulated learning, self-efficacy, metacognition, and student journaling converge on the aforementioned theoretical aspects of this study in terms of conceptual and epistemological change, as well as classroom management and the curriculum used by the study sample.

The foundations of this study were both theoretical and conceptual, consisting of the constructs of personal epistemology, thinking and reasoning, and representational systems—as well as the connections that exist between them and conceptual change, metacognition, self-efficacy, self-regulated learning, and locus of control. Though the study was focused on personal epistemology, the entailments listed herein are given treatment in this chapter in accord with how they influence the study and research questions. Personal epistemology, thinking and reasoning, and representational systems were the central focus of the two research questions that are given in the so-named subsections of the section titled theoretical and conceptual foundations. Metacognition, self-efficacy, self-regulated learning, and locus of control were *factors* of the study environment by virtue of research demonstrating that particular pedagogical and curricular interventions—such as journaling—convey to changes in these same constructs, and are covered in the subsection titled self-efficacy, self-regulation, and journaling. In this way, they served as conceptual foundations for the study in terms of what to expect in the data analysis phase.

The literature review section of chapter two builds on the theoretical and conceptual foundations as they apply first to epistemological and conceptual change in general, and second to how thinking and reasoning within the context of IP conveys to personal epistemological change within that domain, and perhaps in general. This section begins with brief histories of personal epistemology research and the attempts to assess this construct, followed by a discussion of how personal epistemology and conceptual change intersect as fields of research. The remainder of the literature review consists of subsections addressing conceptual change in IP, personal epistemology in IP, and thinking and reasoning in IP classroom settings.

Theoretical Foundations and Conceptual Framework

Personal epistemology. Piaget's cognitive developmental process of equilibration (Piaget, 1970) is—from a historical perspective—central to the theoretical underpinnings of what personal epistemology researchers call epistemological advancement (Bendixen, 2012). Hofer (2004) suggested the concept of epistemic metacognition as a way to understand how students shift beliefs through reflection, while epistemic beliefs also constrain and/or advance conceptual change.

In either case, the domain of knowledge and the educational context determine the direction and magnitude of such transitions in personal epistemology, as well as its overall advancement for the student. Scientific reasoning is naturally recursive by virtue of the fact that empirical investigations challenge the models and hypotheses put forward by scientists—thus forcing the type of declarative metacognition (Hofer & Sinatra, 2010) that influences personal beliefs. IE physics classrooms attempt to simulate the behavior of a scientific *community* by virtue of a discourse that is based on inquiry, collaboration, and consensus building (Bruun & Brewe, 2013; Hestenes, 2010; Irving & Sayre, 2014). Moreover, the very nature of an IE physics classroom relies on leveraging representational systems in order to produce a change in beliefs about the real world through conceptual change. However, in practice, conceptual change interventions differ from epistemological change interventions by virtue of the fact that conceptual change instruction seeks to merely confront and change existing beliefs, whereas epistemological change instruction seeks to influence how beliefs direct learning and the enactment of epistemology in the classroom (Ding, 2014). Epistemic recursion is therefore a key factor in scientific advance, and is one way to understand Hofer's conceptual model of epistemic metacognition—which served as the conceptual framework of this study.

Thinking and reasoning. In the new paradigm for the psychology of reasoning, probability rather than logic, is the rational basis for understanding all human inference (Pfeifer, 2013). Moreover, thinking and reasoning are coupled through the new paradigm in dual-process theories by virtue of the fact that Type 2 (reflective process) thinking is defined as enabling "us to reason by supposition, engaging in hypothetical thinking and mental simulation decoupled from some of our actual beliefs" (Evans & Over, 2013), whereas Type 1 intuitive thinking is fast and automatic concerning the feeling of confidence that accompany answers or decisions (Evans, 2012). Common definitions of the term thinking refer to particular cognitive processes such as transformations of mental representations (Holyoak & Morrison; 2012; Sinatra & Chinn, 2011), or even cognition as a general process (Nimon, 2013), whereas reasoning has become synonymous with cognitive processing in general (Evans, 2012) via memory and reasoning for decision making in social habitats (Rai, 2012). Mulnix (2012, p. 477) conflates the terms thinking and reasoning by stating, “Critical thinking is the same as thinking rationally or reasoning well.” Such definitions are clearly circular, and therefore do nothing in the effort to clarify what is meant by the psychological construct, much less the neuropsychological reality in terms of neurons and various regions of the brain.

Piaget operationalized the construct of thinking in terms of developmental stages, whereas more modern cognitivists adopted an information-theoretic approach based on brain waves, and connectionist notions of neural systems (Peters, 2007). Vygotsky defined it simply as dialog (Fernyhough, 2011). In describing the conceptions of philosophers such as Hegel, Heidegger, Kant, and Wittgenstein, Peters (2007) listed thinking as representation, opinion-making, scientific problem-solving, revealing what is concealed, and concept-making—thereby covering most of psychology in the broadest sense of the term, while giving little by way of specific mechanisms.

These assertions made within the literature suggested a need for greater clarity in defining both thinking and reasoning before any progress can be made in measuring these constructs. However, according to Elder and Paul (2007b), all thinking consists of the following eight elements: the generation of purpose(s), raising questions, using information, utilization of concepts, inference-making, assumption-making, it generates implications, and embodies a point of view. Elder and Paul affirm the common treatment of thinking and reasoning as virtually synonymous terms in their assertion that “whenever we think, we reason” (Elder & Paul, 2007b, “All Humans Use Their Thinking”, para. 2). In other words, thinking is merely a stage of reasoning in the model put forward by Elder and Paul. Reasoning is then defined as a sense-making and conclusion-making process conducted by the mind, based on reasons—implying an “ability to engage in a set of interrelated intellectual processes” (Elder & Paul, 2007b, “All Humans Use Their Thinking”, para. 5), such as the eight elements of thinking already given herein. One distinguishing factor of thinking relative to reasoning in the model offered by Elder and Paul, is that thinking is what agents do when making sense of the world, whereas reasoning is how agents are able to come to decisions about the elements of their thought.

In an attempt to explain how the human mind learns, Elder and Paul (2007a) define thinking in even more general terms as the process by which we take control of the mind in an effort to figure things out. Moreover, these thoughts influence our feelings, and thus the way that we interpret and come to believe various things—in other words, thinking informs our viewpoints. Given the consistency of this model with the general scope of personal epistemology, the models and definitions for thinking and reasoning by Elder and Paul described herein, will serve as a conceptual foundation for what is meant in this study by constructs of thinking and/or reasoning.

The model put forward by Elder and Paul (2007b) contains 35 dimensions of critical thought consisting of 9 affective dimensions, and 26 cognitive dimensions broken into 17 macro-abilities, and 9 micro-skills. Point of view, questioning, assumption making, and using information are four of the eight elements of thought that also appear within the cognitive dimension macro-abilities. Of the remaining four elements of thought, only inference making appears in cognitive dimension micro-skills set. No other elements of thought are clearly listed within the 35 dimensions, although each of the key terms are—for example, the exploration of implications is listed as a cognitive micro-skill, but the ability to generate implications is specified in the eight elements of thought.

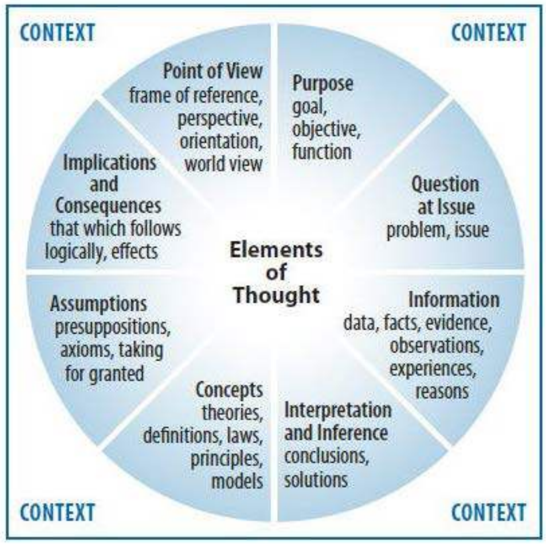

*Figure 1.*The eight elements of thought.
All thought, according to Paul and Elder (2008) consists of eight unique elements that are situated within particular context.

Mulnix (2012) affirms the equivalence of thinking and reasoning that Elder and Paul (2007a) assert, whereas Evans (2012) places thinking at the heart of decision-making and reasoning, as Elder and Paul suggest—in particular, that the process of *thinking* generates the reasons that the process of *reasoning* then bases its conclusions on. Holyoak and Morrison (2012, p. 1) define thinking as “the systematic transformation of mental representations of knowledge to characterize actual or possible states of the world, often in service of goals,” which is essentially goal-directed modeling as defined herein. These convergences in definitions for the constructs of *thinking* and *reasoning* suggest a recent emergence of coherence in the field that is useful for the purposes of this study.

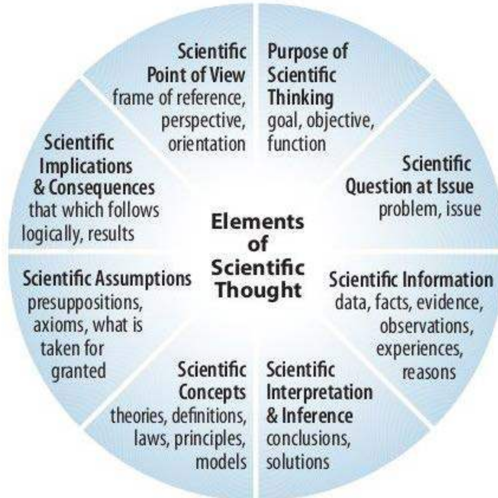

Figure 2. The eight elements of scientific thought.
The general elements of thought remain unchanged when applied in a particular context—such as natural science.
[1]

Building a conceptual model for this study. The transition from general thought to scientific thought is in the specificity of context (Paul & Elder, 2008). In an effort to distinguish thinking from reasoning, the author proposed the following definitions of thinking and reasoning as conceptual bases for coding evidence of the same throughout this study. Thinking is hereby defined as the ability to construct a model—which is one of the items within the elements scientific of thought given by Paul and Elder, called *concepts*. This definition is (1) flexible enough to encompass any representational system, (2) straightforward enough to permit the kinds of frequency distributions and classification schemes that enable direct measurement of this cognitive behavior, and is (3) inspired by the work of PER pioneers cited herein, such as Hestenes, Hake, Redish,

[1] From The Miniature Guide for Students and Faculty to Scientific Thinking (Kindle section title Why Scientific Thinking?), by L Elder and R. Paul, 2008, Copyright 2008 by the Foundation for Critical Thinking... Reprinted with permission.

and Mazur. The term *model* is simply any representation of *structure* (Hestenes, 2010), and structure is a broader term—open to wide interpretation—encompassing the way that interconnectedness between and within systems is articulated. Furthermore, the term reasoning is defined herein as the ability to relate two or more models; and therefore, coordinates the terms in a manner that lends consistency and coherence to the measure of these cognitive behaviors by simply counting attempts. This definition for reasoning is consistent with two of the elements of scientific thought suggested by Paul and Elder: scientific implications and consequences, and scientific point of view.

In the model for scientific thought shown in Figure 2 above, axioms are part of the assumption that are made rather than the result of any process, whereas in Physics, axioms are used in order to generate new ones, as well as being part of fundamental assumptions. Moreover, there are implications and consequences associated with axiom development—also an element of scientific thought—that must be accounted for. The right-hand side of Figure 2 is largely empirical in nature, whereas the left-hand side is rational. To the degree that reasons are generated by thinking about scientific information in the form of data and observations, and if decisions about the interrelatedness of those reasons are what comprise reasoning, then the model for scientific thought put forward by Paul and Elder (2008), already has natural divisions for the constructs of thinking and reasoning as defined herein by the author. Given that the authors definitions are primarily for high-level coding that is consistent with the practice of physics in an IP classroom, the fine-grained distinction put forward in the model by Paul and Elder served as additional theoretical codes used in the data analysis.

Language is the primary means by which human beings encode for meaning. The academic setting of an Introductory Physics (IP) classroom requires an array of *languages*—or what this study calls multiple representational systems (MRS). Words, symbols, graphs, and diagrams encode various kinds of meaning depending on the context of student inquiry. The following section addresses this topic with a view to how encoding for meaning with MRS corresponds to thinking and reasoning.

Representational systems. Representational tools and systems have the capacity to encode information (Fekete, 2010), promote conceptual change (Johri & Lohani, 2011; Johri & Olds, 2011), as well as direct inquiry (Moore et al., 2013), scaffold learning (Eitel et al., 2013), and facilitate the process of knowledge construction (Kolloffel, Eysink, & Jong, 2011). Fekete (2010) suggested that representations are simply the realization that there exists an isomorphism (one-to-one relationship) between the conceptual/perceptual domain, and the *activity space* where representation occurs. Activity spaces are technically defined as “spatiotemporal events produced by dynamical systems” (Fekete, 2010, p. 69), and neural systems in the human brain mimic those dynamical systems to some degree. The dynamical systems approach is conceptually equivalent to using most any marker, or token, to describe one thing in terms of another—which is the general practice of Physics (Plotnitsky, 2012; Wu & Puntambekar, 2012).

Hestenes (2010) deployed multiple types of representations for encoding structure in terms of systemic (links among interacting parts), geometric (configurations and locations), object (intrinsic properties), interaction (causal), and temporal (changes in the system) as ways to model and categorize the observation that students of science make in an effort to mimic the expert view. In these ways, MRS are instrumental for modeling the structure of physical phenomena, and therefore serve as evidence of what students believe the varied representational conventions of mathematics and physics are capable of describing. Their status as mechanisms of epistemological change is the primary research question at hand.

Waldrip and Prain (2012) have qualitatively tested an intervention that relies heavily on representational systems in an effort to promote scientific reasoning as a cognitive activity that involves thinking by means of constructing representations, and subsequently judging them for their efficacy—which under the model for scientific thought proposed by Paul and Elder (2008), is both thinking by representation, and reasoning through judgment of those thoughts. The results they obtained indicate that an interactive environment where observed phenomena are tested and re-tested, represented and re-represented, and evaluated through group collaborations that give opportunities to defend and judge hypotheses, positively influences student confidence and engagement. The distinction that Fekete (2010) offers in terms of how representations relate to their encodings is part of the conceptual basis for thinking and reasoning as defined by Paul and Elder (2008), and described in learning environments by Waldrip and Prain (2012). Moreover, the features of models in Physics—such as systemic, geometric, object, interaction, and temporal (Hestenes, 2010)—serve as very particular and fine-grained conceptual distinctions to be coded for in the qualitative analysis of student artifacts in this study.

Prior knowledge influences the top-down thinking and reasoning that students bring to learning habitats where new information found therein is designed to promote bottom-up forms of thinking and reasoning for conceptual, and potentially epistemological change. However, as shown in the next section, epistemic beliefs are strong motivators for and against self-regulated learning. In other words, certain beliefs either promote or stifle the types of thinking and reasoning that are required for learning.

Self-efficacy, self-regulation, and journaling. The epistemic beliefs that students have concerning the development of scientific knowledge directly influence the acquisition of that knowledge, and therefore the achievement that shepherd self-concept and self-efficacy when learning in the scientific domain (Mason, Boscolo, Tornatora, & Ronconi, 2012; Sawtelle, Brewe, Goertzen, & Kramer, 2012). Cassidy (2011) points out the fact that academic control is one factor within the complex of self-regulated learning that competes with a student's self-evaluation—such as the belief that learning is dependent on the amount of struggle involved with academic endeavors and inborn traits such as intelligence (Koksal & Yaman, 2012). Achievement gaps narrow in classrooms where extensive reading and writing are organic to an engaging experience that contributes to enhanced motivation, self-efficacy, and locus of control—which are essential components of active learning and achievement in academic settings (Kennedy, 2010). Moreover, the likelihood that a student will deploy any particular representational medium—journal or otherwise—depends on factors such as motivation, goal orientation, self-regulation, and general interest in the domain of knowledge relevant to the setting (Bodin & Winberg, 2012; Kennedy, 2010). Therefore, providing students with an opportunity to defend their strategies through discussion and written journals is helpful in promoting the kinds of self-advocacy that catalyzes self-regulated learning (Cifarelli, Goodson-Espy, & Jeong-Lim, 2010; Muis & Duffy, 2013). Furthermore, metacognitive monitoring, self-efficacy, and self-regulated learning are optimized when the epistemological domain of a learner and the epistemology of the domain focus are matched—such as a rationalist in a mathematics setting (Muis & Franco, 2010).

The aforementioned findings served as a broad conceptual and theoretical foundation for this study by virtue of the fact that data collection and pedagogy within the study environment match the general features described therein. Journaling and collaboration are the central features of the classroom environment where thinking and reasoning with MRS is being deployed. Muis and Franco (2010) linked metacognitive monitoring, self-efficacy, self-regulated learning, and epistemology in ways that are consistent with Hofer's epistemic metacognition model (Hofer, 2004)—which also served the overarching conceptual framework for this study. The connections that exist between metacognition, epistemology, and self-regulated learning (Barzilai & Zohar, 2014; Greene, Muis, & Pieschl, 2010) are relatively new in the literature (Hofer & Sinatra, 2010), but nonetheless warranted attention in this study given their connections to the primary data collection method of student journals.

Convergence of conceptual and theoretical foundations. The expression of epistemic beliefs is typically expressed in the form of language. Within the field of Physics—and thus an IP classroom—MRS serve as the languages by which a learner is able to encode for meaning, and therefore transmit in writing or in narratives their own epistemic stance. Thinking and reasoning are unavoidable cognitive activities for both conceptual and epistemological change, and are necessarily metaphorical, empirical, and rational in the context of Physics. The efficacy of journal activities to generate self-efficacy and self-regulated learning through metacognitive monitoring (Muis & Franco, 2010), while simultaneously affording the author-researcher a corpus of student artifacts employing MRS, provides an equally fertile source of data for analysis of student thinking and reasoning. In these ways, the model for scientific thought (Elder & Paul, 2007b) corresponds with the advance of self-efficacy and self-regulation that is consistent with epistemic change in scientific domains of knowledge (Mason et al., 2012; Muis & Duffy, 2013; Sawtelle et al., 2012). Moreover, the use of journals and interviews provides ample opportunity for the kinds of student reflection that reveal the connections between conceptual and epistemological change through what Hofer (2004) described as epistemic metacognition.

Review of the Literature

A brief history of personal epistemology research. Personal Epistemology (PE) has been an expanding field of inquiry for at least 40 years, with the coalescence of a handful of models and theories emerging in the late 1990's to early 2000's—such as process and developmental models (Bendixen, 2012), and at least four different assessment instruments for judging the epistemic state of learners at most any age (Hofer & Pintrich, 2012). Student beliefs about knowledge are multidimensional and multilayered, such that the nature of knowledge itself can be described along the dimensions of certainty and simplicity, whereas the dimensions source of knowledge and its justification describe the nature of *knowing* (Hofer & Pintrich, 2012; Mason, Boldrin, & Ariasi, 2010). Epistemological beliefs are simply beliefs about what knowledge is and how it is obtained (Richter & Schmid, 2010), and are a form of declarative metacognitive knowledge (Hofer, 2004). Richter and Schmid (2010) distinguish epistemological metacognition from psychological metacognition in terms of their differing content—

where psychological metacognition refers to mechanisms of memory and learning, and epistemological metacognition refers to the process by which knowledge is qualified.

Multiple lines of research into personal epistemology in student populations indicates that *fine-grained* cognitive resources better explain the formation of beliefs about learning than do developmental stages, or belief-systems (Hofer & Pintrich, 2012). Naïve epistemologies are proposed to precede sophisticated ones developmentally—such that the natural progression of knowledge as facts justified by authority (naïve) is transformed into a more complex and nuanced network of ideas (sophisticated) that are understood socially and contingently, and subsequently result in higher achievement (Bromme et al., 2010). However, Bråten and Strømsø (2005) found that naïve epistemology produces better results when the topic at hand is unfamiliar and complex—thus compelling the epistemological framework to rely on authority—whereas a more sophisticated epistemology relying on knowledge as a more personal and subjective construction is more likely to misconstrue the textual evidence under analysis. Sophisticated epistemologies as the means by which learning is positively influenced is contingent on the context of the task and the level of expertise that task participants possess (Hammer & Elby, 2012). Both context and skill place particular kinds of demands on the deployment of representational systems in accordance with the epistemic beliefs that students possess with respect to the capacity of those systems to encode meaning.

Developmental models such as the epistemological reflection model (Baxter Magolda, 2012) offer a constructivist viewpoint for understanding the mechanism(s) for epistemological change, whereas process-model theorists consider more fine-grained cognitive resources than developmental stages or beliefs (Bendixen, 2012) as a means for explaining epistemological advance. Finer-grained resources include particular views about knowledge in general, acquisition of said knowledge, the kinds of and interrelations of knowledge types, and the sources of that knowledge. Bendixen and Feucht (2010) offer an integrative model that attempts to capture the clear findings of both the developmental and cognitive branches of the field, by framing the mechanism of change as having three distinct components: epistemic doubt, epistemic volition, and resolution strategies. Epistemic doubt (cognitive dissonance related to beliefs) and epistemic volition (the will to change) work in concert towards epistemological advance (Rule & Bendixen, 2010). Resolution strategies are simply reflective, socially interactive, retrospections by which a person analyzes the implications of personal belief (Baxter Magolda, 2012; Bendixen, 2012).

Domain-general and domain-specific epistemologies are distinct factors that influence learning (Lee & Chin-Chung, 2012; Schommer-Aikins & Duell, 2013). In a study involving 701 college students in the United States, researchers used path analysis to determine that domain-general beliefs have an indirect effect on performance, whereas domain-specific (mathematics) beliefs have both direct and indirect effect on mathematical problem solving. The beliefs that are formed within the context of a particular domain influence thinking and reasoning more dramatically than do domain-general beliefs that apply to all situations. For example, the belief that the average person learns quickly or not at all was strongly correlated with a weak mathematical background due to choices influenced by the belief that mathematics is not useful or accessible. Moreover, the opposite was also found to be true—that a belief that mathematics takes time to learn and is useful is consistent with the practice of taking more mathematics courses and devoting the diligence to them that accompanies successful skill development (Schommer-Aikins & Duell, 2013).

While few researchers in the field of personal epistemology doubt the reality of development stages for epistemological advance, the evidence of domain-specific processes and environments is the primary reason that the majority of attention has shifted to the mechanisms of epistemological change in terms of psychological constructs—such as thinking and reasoning (Hofer & Pintrich, 2012). Strategies for resolving epistemic doubt (Bendixen & Feucht, 2010) and the implications of and on personal beliefs (Bendixen, 2012) are metacognitive and epistemological in nature (Barzilai & Zohar, 2014; Hofer, 2004; Richter & Schmid, 2010), and require some level of social interaction and individual analysis, as well as a positive affective backdrop from which motivation leads to concentration and control in problem-solving settings (Bodin & Winberg, 2012; Muis & Duffy, 2013). With respect to this study, the context of epistemological advance is scientific, and therefore the thinking and reasoning is as well (Paul & Elder, 2008).

A brief history of assessment on personal epistemology. One of the earliest attempts to psychometrically measure personal epistemology was the Psycho-epistemological Profile (PEP), which measures the construct on three dimensions: Rational, Empirical, and Metaphorical (Royce & Mos, 1980). The rational dimension of PEP assumes that knowledge is obtained through reason and logic, whereas the empirical dimension derives and justifies knowledge through direct observation. The metaphorical dimension of PEP *sees* knowledge as derived intuitively with a view to subsequent verification of its universality. The PEP instrument has demonstrated concurrent validity based on examination of group scores and their correspondence to the underlying theory (Royce & Mos, 1980). For example, biologists and chemists were typically strongest on the empirical dimension of PEP, whereas persons situated in the performing arts were more metaphorical in nature—just as mathematicians tend to be more rational than any of the other two PEP dimensions. Furthermore, the construct validity of the PEP has obtained moderate to moderately high correlations at the $p = 0.05$ level for the Myers-Briggs Personality Test, and the MMPI (Royce & Mos, 1980).

Royce and Mos (1980) also reported positive correlations for each item on the PEP with the total score in its dimension. Split-half reliability coefficients on two forms of the PEP indicate satisfactory homogeneity with correlations of $r = .75$, .85, and .76 corresponding to the rational, metaphoric, and empirical dimensions, respectively, for a sample of $n = 142$ students on form V of the test given in 1970, versus correlations of $r = .77$, .88, and .77 for a sample of $n = 95$ students on form VI (current form) given in 1975. Test-retest reliability coefficients for the PEP in two small sample studies are given as follows: junior college students ($n = 19$) tested over a three-month period obtained reliability coefficients of $r = .61$, .78, and .67 on the rational, metaphoric, and empirical dimensions, whereas first-year university students ($n = 43$) tested over a nine-month period obtained reliability coefficients of $r = .68$, .66, and .87 on the rational, metaphoric, and empirical dimensions, respectively. The moderately high inter-correlations between dimensions of the PEP indicate considerable dependence between these epistemic styles; however, the relative degree of independence suggested their existence as separable and meaningful dimensions of personal epistemology (Royce & Mos, 1980).

The Epistemological Questionnaire (EQ; Schommer, 1990), the Epistemic Beliefs Inventory (EBI; Schraw, Bendixen, & Dunkle, 2012), and the Epistemological Beliefs Survey (EBS; Wood & Kardash, 2012) are the three most studied assessments of personal epistemology to date (DeBacker, Crowson, Beesley, Thoma, & Hestevold, 2008). Schommer's approach broke with the tradition of developmental structure models to a system of independent dimensions pertaining to beliefs *about* knowledge and knowing rather than strictly held beliefs. The structure of knowledge as simple vs. complex, whether or not knowledge is certain, how personal authority and locus of control determine knowledge, the speed at which learning is possible, and how fixed or malleable learning truly is, comprise Schommer's dimensions of personal epistemology. She created a 63-question instrument with 5 dimensions and 12 subsets within the same. In her original study, the four factors of Simple Knowledge, Certain Knowledge, Innate Ability, and Quick Learning emerged; however, the fifth dimension of Source of Knowledge did not (Schommer, 1990). Subsequent studies have had inconsistent replications of Schommer's factor extraction due to abridged versions of the original instrument, and comparing subscales rather than items in factor extraction processes (DeBacker et al., 2008). Moreover, attempts to replicate suffer from small sample sizes, and a tendency to find different factors and number of factors that while clearly related to Schommer's original 5 dimensions at face value, are nonetheless structured differently.

The EBI was created in response to these issues and had initially obtained consistent factor extractions in studies by Bendixen, Schraw and Dunkle (1998) and Schraw et al. (2012) that seemed to preserve the 5-dimension structure originally proposed by Schommer (1990). However, Nussbaum and Bendixen (2003) could obtain only three interpretable factors in their study (n = 238) of the EBI: Simple Knowledge (α = .69), Certain Knowledge (α = .69), and Innate Ability (α = .77). With respect to internal consistency across the paper-based, computer-based, or web-based delivery modalities, Chronbach's Alpha scores ranging from .42 to .79 were found with sample sizes of n =67 and n = 101 (Hardré, Crowson, Kui, & Cong, 2007). Though an improvement on the EQ, these findings reveal modest correlations within relatively low sample sizes, indicating the need for continued research in the assessment of personal epistemology (Hofer, 2012).

In two samples (n = 417, n = 378), confirmatory factor analysis (CFA) revealed a poor fit to the 5 dimensions of the EBI in both sample groups, and internal consistency coefficients were consistently below .70 (DeBacker et al., 2008). The EBS was tested on two sample groups (n = 380, n = 415) with only marginal increases in internal consistency falling below .80 (DeBacker et al., 2008). Low correlations between only two dimensions of the EQ within all 6 subscales indicate low reliability among the subscales themselves. For these reasons, and others, DeBacker et al. (2008) argue that the entire enterprise for assessing personal epistemology has suffered from a purely empirical approach that has not been properly grounded in theory, and suggest that researcher within this field more clearly define and clarify epistemic beliefs from beliefs about those beliefs. Hofer (2012, Kindle location 409) sums it up clearly by stating, "we need considerably more effort addressed toward either unifying our language or clarifying our existing distinctions in terminology, improving methodological approaches so that comparable studies can be conducted, and in considering the relation between epistemological understanding and other key constructs." It is assumed within this study that thinking and reasoning qualify under the heading of *other key constructs*.

The Colorado Learning Attitudes about Science Survey (CLASS) instrument was designed to measure epistemic stance of students with respect to student knowledge of, and learning of, Physics (Douglas et. al, 2014). Averaging the number of responses that agree with the pre-determined expert view is the method by which the percent favorable score is assigned to a student completing the CLASS survey. The instrument consists of 42 questions distributed in 7 categories: personal interest, real world connections, conceptual connections, applied conceptual understanding, problem solving general, problem solving confidence, and problem solving sophistication. In spite of the robust validation of this instrument using over 7,000 respondents since 2003, interviews, and factor analysis, the CLASS instrument was deemed unsuitable for this study due to its emphasis on problem solving and conceptual change—two dimensions of learning beyond the scope of this study, as well as an unstable factor structure (Douglas et al., 2014).

Regardless of the state of affairs in assessing personal epistemology, the PEP instrument was ideal for the purposes of this study for at least two reasons: its rational, empirical, and metaphorical dimensions match the practice of science in general, and physics in particular (Lancor, 2012; Lee & Chin-Chung, 2012; Plotnitsky, 2012), as well as the fact that it does not suffer from any of the reliability issues that other instruments obtain as described herein. Moreover, as the research questions were not concerned with the direction of epistemological change, neither are the dimensions of the PEP.

Connections between conceptual change and personal epistemology. The histories of both conceptual change and epistemological change research span approximately 40 years each, and are just beginning to reach a point in the most recent decade where theoretical and methodological coherence are feasible (diSessa, 2010; Hofer, 2012). The sometimes intersecting histories of both fields is worthy of brief exploration in this review of the literature, as both fields have major contributors whose research occurred in mathematics and physics classrooms such as the one proposed in this study. This section describes the major connections that exist between conceptual change and epistemological change with an emphasis consistent with the research questions addressing epistemological change through thinking and reasoning with MRS.

Thomas Kuhn first introduced the terminology of *conceptual change* in his landmark treatise *The Structure of Scientific Revolutions* in reference to how concepts embedded within a scientific theory change when the theory (or paradigm) underlying them changes (diSessa, 2010). Historically, the process of conceptual change in educational settings was though to consist of (a) conceptual dissatisfaction, (b) the recognition of new and intelligible conceptions that are (c) plausible, and (d) perceived as fruitful for progress (Posner, Strike, Hewson, & Gertzog, 1982). This classical model became understood as cognitive conflict strategy (CCS) and ultimately failed as an instructional strategy because student learning was found to be a gradual process that is influenced by affective and motivational factors that are contingent on personal epistemology (Lee & Chin-Chung, 2012).

The framework theory of conceptual change asserts that naïve theoretical frameworks for understanding the world are difficult to change because everyday experience affirms their perceived stature in spite of the felt conflict that persists between their content and that of conventionally accepted theories (Vosniadou, Vamvakoussi, & Skopeli, 2010). Conceptual change can be achieved through bottom-up additive mechanisms such as the acquisition of new information through experience, or through top-down mechanisms such as instruction-induced conceptual change (Vosniadou, 2007). Additive mechanisms for conceptual change produce synthetic models consistent with assimilation and accommodation processes (Piaget, 1970), and lack the sort of meta-conceptual basis that instruction-induced frameworks are capable of providing (Vosniadou, 2007). Metacognition is central to the awareness that one's personal naïve theory is in conflict with another theory, and therefore productive in both conceptual and epistemological change (Barzilai & Zohar, 2014; Bendixen, 2012; Chang, Wen, Kuo, & Tsai, 2010).

The process of building models is commonly understood as a means for assessing our understanding of one or more theories, which thereby forces a reconciliation of naïve personal theory with conventionally understood theory (Hestenes, 2010; Jonassen, 2010). In contrast to classical conceptual change theories, the framework hypothesis is theoretically constructivist in nature, and views misconceptions as "dynamic, situated, and constantly changing representations that adapt to contextual variables or to the learners developing knowledge" (Vosniadou, 2007, p. 60).

Moreover, these models are representative of ontological categories pertaining to substance and process—as well as epistemological ones concerning the domain of inquiry. However, it is still unclear at the present time whether or not conceptual change consists of discrete (knowledge-in-pieces model) comparisons, or continuous (coherence model) bits of knowledge that are connected structurally by the relations that make them meaningful on a larger scale (diSessa, 2010). According to Inagaki and Hatano (2010), conceptual change involves a complete restricting of knowledge systems in general because it involves not only individual concepts, but also how those concepts stand in relation to rules, models and personal theories. Measuring conceptual change is one of the fundamental and persistent problems in cognitive psychology; however, the difference between spontaneous conceptual change and instruction-induced conceptual change is rooted in the intentional efforts of a cognitive agent to resolve the incongruity within their knowledge system (Inagaki & Hatano, 2010). Part of the trouble in measurement of conceptual change is in tracking how a change in the truth-value of one *piece* of knowledge corresponds to changes in related *pieces* of knowledge—which simply highlights the difference between the knowledge-in-pieces versus coherence viewpoints, which dominate the field of conceptual change.

Clement (2010) describes the longstanding gap at the core of conceptual change theory in terms of how the mechanisms of conceptual change are presently unknown, even though the conditions for, and effects of conceptual change are. According to Clement (2010), part of this problem rests in defining what a model is, and distinguishing the features of a mental model from external representations of that mental model. Both Clement (2010) and Fekete (2010) distinguish the features and existence of a mental model from external representations that persons make of those mental models. Nersessian (2010) offers a definition of mental model as an abstract conceptual system used for reasoning, which idealistically represents the salient features of a physical system through the use of surrogate objects to which the cognitive agent imparts properties and behaviors. However, the conceptual change process associated with any model varies widely in scope—such as a complete paradigm shift, model synthesis, major model modification versus minor model revision, concept integration and/or differentiation, bridging analogies, and new model construction.

Though this study had a singular focus on epistemological change in terms of MRS used in thinking and reasoning processes, conceptual change is expected for all of the reasons, and in the ways described herein (Chang et al., 2010; Lee & Chin-Chung, 2012). One consistent theme shown in these research findings is that conceptual change depends on the restructuring of knowledge domains in terms of the relationships that exist between models (diSessa, 2010; Inagaki & Hatano, 2010), as they produce changes in personal, and sometimes naïve theories (Jonassen, 2010; Vosniadou, Vamvakoussi & Skopeli, 2010). Nersessian (2010) specifies the mechanism for conceptual change as model-based reasoning capable of producing paradigm shifts, model revision/integration/synthesis, and new model construction. Each of Nersessian's metrics are consistent with the elements of scientific thinking given by Paul and Elder (2008), and thus represent specific targets for analysis in this study.

Conceptual change in introductory physics. Under the premise that conceptual change and scientific reasoning are sequentially fixed with respect to development of problem-solving skills, Physics Education Research (PER) pioneers created the Force Concept Inventory (FCI) as a means for assessing the Newtonian force concept in a student's understanding before and after instruction, (Hestenes, 2010). The most successful reforms arising from PER include Interactive Engagement (IE) approaches such as Peer Instruction (Gok, 2011; Wood, Galloway, Hardy, & Sinclair, 2014), and

Modeling Instruction (Hestenes, 2010). Both the FCI and the Mechanics Baseline Test (MBT) are used widely within the PER community in order to assess the effectiveness of IE techniques relative to the teaching and learning of introductory physics courses (Hake, 1998)—as is Lawson's Classroom Test of Scientific Reasoning (CTSR) for general scientific reasoning (Coletta et al., 2007a). According to Coletta and Phillips (2010), IE techniques are able to produce measurable changes in scientific thinking and reasoning that exceed the kinds of assessment gains normally obtained through traditional instruction—such as the fact that students in IE classrooms obtain an average normalized gain on the FCI that is more than twice that of the traditional students (Cahill et al., 2014; Hake, 1998; Rudolph et al., 2014).

The FCI has been shown to define a unidimensional construct distinguishing non-Newtonian and Newtonian populations, where the defining concept that separates the two is the idea that no net force is required in order to maintain constant velocity (Planinic, Ivanjek, & Susac, 2010). However, using Rasch analysis techniques on the FCI, differential item functioning (DIF) analysis revealed that two different groups with equal ability were not able to consistently answer certain FCI questions in the same way—suggesting that the construct changes slightly from pre- to post-test. According to Planinic et al., the width of the FCI as it pertains to the concepts covered is too narrow for the proper discrimination in the range of abilities relative to the construct. The authors suggest a number of improvement including two different test (pre- and post-) that share a common set of items, as well as simply removing items from the middle of th test and adding entirely new ones at the extremes. Moreover, the authors stress that the FCI is still a useful test for assessing the efficacy of instruction relative to the Newtonian force concept (Planinic et al., 2010).

Yasuda and Taniguchi (2013) determined that 2 of the 30 FCI questions were invalid by using a series of sub-questions in order to validate whether or not the learners actually possessed the conceptual knowledge required to answer the original items. By combining the results of testing for both false positive and negatives in student response patterns, as well as the validity of the sub-questions, Yasusa and Taniguchi were able to find a significant difference ($\alpha = 0.05$) between the pre- and post-test conditions. This study did not extend beyond the two questions under study, and the researchers suggest that further research is required in multiple populations internationally, as well as for the rest of the FCI test items. These findings suggest a source of systematic error that has the potential to reform current understanding of the usefulness and import of the FCI as an instrument that has shaped PER for several decades now (Yasuda & Taniguchi, 2013).

Wang and Bao (2010) developed the FCI-metric as a way to assess IP student proficiency based on the FCI score. These researchers used a 3-parameter Item Response Theory (IRT) model based on data obtained at Ohio State University from 2003 to 2007. The pre-test data consisted of 2,802 students and the post-test data included 2,729 students. Eigenvalue analysis of the correlation matrices of pre- and post-test conditions of the FCI in this sample a single proficiency variable (unidimensionality) for all 30 items on the FCI. However, interpretation of the fit between the assessment model and the underlying cognitive model is subject to systematic variations that occur within the assessment model—in particular, which of three particular IRT models are used (Chen et al., 2011). In their analysis, Chen et al. used archived data from 3,139 participants with each of three 3-parameter logistic models: R, MULTILOG with pre-processing, and MULTILOG without pre-processing. Though each method produces consistent results, the variation between proficiency and ability parameters may lead to misunderstandings in certain contexts. The researchers suggest further analysis in order to determine more precisely which of the models is best, and within what context it should be used (Chen et al., 2011).

The Force and Motion Conceptual Evaluation (FMCE) assesses fluency with verbal and graphic representations of just the force concept and one-dimensional kinematics, as opposed to the FCI's broadened focus including verbal and pictorial two-dimensional motion, vectors, Newtonian forces, and mechanical systems in general (Thornton, Kuhl, Cummings, & Marx, 2009). Though FCI and FMCE scores have a strong positive correlation (r = 0.78), students who perform well on one do not necessarily perform well on the other; and therefore the use of both assessments in various instructional settings reveals important features of instruction and the use of representational systems and how those factors convey to student learning (Thornton et al., 2009). In a study involving 3,420 students at 13 different institutions, pre-test and post-test test scores for the FMCE revealed a 65% ±6 normalized gains for IE methods versus a 15% ±3 gain for traditional methods.

Interactive Engagement (IE) techniques alone are not always the source of conceptual change. In a study involving 2,537 undergraduate students taking a second-semester IP course in electricity and magnetism at four major universities, student conceptual gains on the Brief Electricity & Magnetism Assessment (BEMA) for the groups using a particular curriculum—Matter & Interactions (M&I) textbook and labs—

outperformed traditional students by a factor of 2 (Ding & Caballero, 2014). The M&I curriculum reorganizes content and place an emphasis on microscopic cause and effect patterns, as well as providing lab opportunities to develop simulations in a programming environment, whereas traditional methods emphasize standard textbook content and conventional labs involving strictly physical apparatus. Analysis of time devoted to lecture topic areas found that there were no significant difference between traditional and reformed curriculum, thus emphasizing the difference in content and emphasis.

Decades of PER have established that certain pedagogies obtain better conceptual gains than others—namely, IE methods outperform traditional methods (Hake, 1998). The study environment described herein is an IE reformed pedagogy with ample opportunity for students to express and use concepts in collaborative way. Moreover, many of the assessments created by the PER community to measure conceptual change are used by the author-researcher, and are therefore material to the overall discussion concerning the relationship between conceptual and epistemological change.

Personal epistemologies and learning physics. Epistemic beliefs have the capacity to bias the learning of students towards preferred types of information and learning environments (Muis, Kendeou, & Franco, 2011). Student epistemologies have been shown productive in their capacity for transfer from physics to other domains of knowledge—such as mathematics (Forsyth, 2012; Po-Hung & Shiang-Yao, 2011), but not necessarily from mathematics back to physics (Po-Hung & Shiang-Yao, 2011). In their study, Po-Hung and Shinag-Yao noted that students of mathematics based their interest to learn in physics on their belief in the capacity of mathematics to prove things versus what physics is able to demonstrate. Though students believed that the fields of mathematics and physics are intimately related, their beliefs about the types of knowledge that each field conveys determined not only personal interest, but also the degree to which those connections would be promoted in their teaching practice after college.

Ding (2014) found two factors that influence student conceptual gains in IP: pre-existing scientific reasoning skills, and pre-instructional personal epistemology. Path analysis was used to confirm the existence of a “direct causal influence” of pre-instructional personal epistemology and conceptual learning in IP (Ding, 2014, p. 5). In this study consisting of 167 first-year calculus-based IP students at a university Eastern China, the FCI, CTSR, and the CLASS instruments were given as pre- and post-instruction tests. The structure of the classroom environment was a traditional lecture format where the instructor made no efforts to promote or probe student epistemologies. The CTSR scores of this sample population were typical in incoming college freshman, whereas the FCI normalized gains were above average at 52.1% ±18.9. In this study, the researcher cautions that the small-to-moderate path strengths obtained between pre-instructional epistemology and conceptual gains confirm the veridicality of the model, but fall short of providing a strong, causal proof. Ding (2014) recommends further research in classroom settings where instruction cultivates student reasoning and epistemological growth. In a similar study, Bodin and Winberg (2012) noted that in addition to prior knowledge and epistemological beliefs, locus of control and positive emotions associated with concentration serve to enhance and predict performance.

The Maryland Physics Expectations (MPEX) survey of epistemological stance in IP measures epistemological attitudes and beliefs along six dimensions: independence, coherence, concept, reality link, math link, and effort link (Sharma, Ahluwalia, & Sharma, 2013). The Coherence dimension refers to the degree to which a student perceives the topic as disjointed pieces versus a continuous hole, the Concept dimension of the MPEX-II refers to how students sees concepts as merely cues towards a formula versus a substantive description of reality, and Independence refers to whether or not the student place authority in their own understanding or in an external source such as a teacher or textbook. The reality link attempts to discern whether or not students see ideas in physics are relevant to real life, whereas the math link probes the students' view of math as disconnected from physics versus representative of it. The effort link merely gauges how diligently students attempt to use information and make sense of it. Sharma et al. (2013) found that undergraduate students in the United States, Thailand, Turkey, and India tend to become more entrenched in their novice-like views of physics due to a full year of traditional instruction. The only exception to this trend was in master's degree students, who presumably had greater interest in the field due to their voluntary election to pursue graduate work in physics. The general conclusion of these researchers is that an indifference in teacher attitudes about the relationship between students and instructors leads to a mediocre at best learning experience that tends to drive students away from science.

A truncated version of the MPEX survey of epistemological stance in IP —the Maryland Physics Expectations-II (MPEX-II)— was found to be psychometrically unreliable in a large study of 505 Turkish high school students in IP (Yerdelen-Damar, Elby, & Eryilmaz, 2012). The source of its shortfall in reliability is due to the fact that there are at least two perspectives from which to interpret the correlations between items in each dimension of the survey—the beliefs perspective or the resources perspective. A beliefs perspective understands epistemology in developmental stages and/or naïve versus expert theory construction, whereas the resources perspective understands epistemology as a context-dependent construct deployed in accordance with the setting that a student is situated. The MPEX-II has only three dimensions: Coherence, Concept, and Independence. Two out of three factors on the survey fell below the 0.70 thresholds for reliable Cronbach's alpha due to weak correlations among items within those dimensions. Interpretation based on the beliefs perspective suggests that the instrument failed to measure the actual student beliefs, whereas the resources perspective suggests that the details in the survey items serve to activate distinct epistemological resources. The main finding of Yerdelen-Damar et al. (2012) was that the MPEX-II is structured to be understood from the beliefs perspective, and is therefore partisan with respect to competing theories of epistemological growth.

Epistemological resources include calculations, physical mapping, invoking authority, and mathematical consistency (Bing & Redish, 2012). Physical mappings differ from calculations by virtue of how consistent the symbols and diagrams are with the physical properties of a system, whereas, calculations are simply algorithms that lead to trustworthy results. Moreover, the epistemological resource of invoking authority further relies on implicit trust in a source of knowledge—such as an instructor or textbook from which physical mappings and algorithms are given. Bing and Redish (2012) lend these four epistemological resources based on the analysis of over 150 hours of videotaped discussions of upper-division physics students arguing for or against claims disputed in a classroom setting. Each of these epistemological resources served as warrants for the beliefs held by students engaged in conflict resolution of physics problems.

Bodin (2012) used network analysis to study the epistemological framing of physics students engaged in computational physics problem solving in order to generate graphical representations of epistemic framing before and after a problem-solving episode. The elements within the epistemic frame proposed by Bodin consist of knowledge, beliefs, and skills. In the process of solving numerical problems within a computational environment, the shift in epistemic framing revealed in the before and after conditions indicated both conceptual change and the construction of new knowledge for those students. According to Bodin (2012), these findings suggest that assignments structured to mix competencies and skills from multiple disciplines facilitates the construction of new knowledge, and thus a shift in epistemic framing that inevitably progresses from naïve to expert over time.

Epistemological framing is a problem common to classroom environments where students *frame* the problem-solving activity as an answer-generating one rather than a knowledge construction one (Hutchison & Elby, 2013), and where group discussions are an integral part of the course design (Irving, Martinuk, & Sayre, 2013). Moreover, epistemological framing is a tool by which learners make sense of current problems in light of prior experience (Hutchison & Elby, 2013). In their study, IP students were asked a *think-aloud* question about two projectile motions, where all variables were the same except the initial condition. Perceiving that the question had a straightforward answer in terms of simple facts, many students misinterpreted the question and answered wrong. When the researcher focused their attention on the salient aspects of the situation, all students quickly realized their mistake and reasoned correctly to the right answer. A control group of students inexperienced with Physics were asked the same questions, and all reasoned intuitively towards the correct answer because they did not *frame* the question as an opportunity to simply recall textbook-level facts.

Bing and Redish (2012) described the components of epistemological framing as social, artifacts, affect, and epistemology. The social component of an epistemological framework describe the *who* and the *how* of interactions within groups. Artifactual components refer to materials used in the process of problem-solving, whereas the component of affect deals strictly with how an individual feels about those activities. The epistemology component of an epistemological frame refers to the means by which an individual constructs new knowledge. The authors use epistemological resources and epistemological framing as the basis for an ontology of student cognition in physics capable of describing the elements of student thinking and reasoning therein. Bodin (2012) describes this sort of epistemological framing as the activation of a network of epistemological resources, where the network is the ways in which knowledge, beliefs, and skills are organized within context. Furthermore, Bing and Redish (2012) suggest that analyzing student work in terms of epistemological resources and epistemological framing provides a way to assess a student's transition from to novice to expert condition by virtue of what they call a journeyman stage where thinking and reasoning are coupled with diligent efforts to coherently justify the knowledge that they are actively constructing.

Hammer and Elby (2012) suggest an ontological approach to forming an adequate theory of epistemological change in terms of the resources that are (1) productive for that change as they are (2) situated within the context that students actually use them. This changes the traditional focus of simply cataloging how student epistemologies differ from the experts, to probing the unexplored domain of epistemological resources, and their capacity to produce epistemological change. Representational systems are one such resource, and the content of MRS in Physics is neither purely rational nor empirical, but also depends on metaphorical representations—such as the term *flow* for energy transfer, light is a *particle/wave*, and electrons *tunneling* through quantum spaces—in order to foster the understanding of complex phenomena and their underlying theories (Brewe, 2011; Lancor, 2012; Scherr et al., 2012; Scherr, Close, Close, & Vokos, 2012). For example, the conventional language of physics has proven productive in the hands of expert physicists; however, due to its metaphorical nature, it is a source for conceptual confusion among students (Hammer & Elby, 2012) because the common everyday notions of force and motion held by laypeople, are rarely what physicists are referring to in their models (Hestenes & Wells, 1992).

A pseudo-longitudinal study of last-year high school student's ($N = 157$), year 1 – 5 undergraduate students ($N = 406$), and post-doctorate researchers or university professors ($N = 74$) in the United Kingdom indicated no significant change in attitude towards Physics during the undergraduate experience using the Colorado Learning Attitudes about Science Survey (CLASS) instrument (Bates, Galloway, Loptson, & Slaughter, 2011). There were, however, significant changes in level of expert-like thinking as measured by the CLASS instrument at the entry and exit points of the undergraduate program, which researchers attribute to a selection effect reflecting levels of personal interest, as well as approximately 15% of last-year students intending to major in Physics must take an entrance exam for university admission. In a large-scale study of Chinese middle ($N = 521$) and high school students ($N = 797$), results showed that traditional lecture-based instruction in Physics over a three-year period, produces a reduction in expert-like views in Physics (Zhang & Ding, 2013). One exception to this trend was in grades 9 and 12 where changes in content, sequence, pace, and external motivations produce slight increases in expert-like views of Physics. Researchers hypothesized that both pedagogical and non-pedagogical factors influence the complex interaction between formal instruction and personal epistemology in Physics.

The Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS) instrument was developed for the sake of assessing epistemology and expectations in IP laboratory settings (Zwickl, Hirokawa, Finkelstein, & Lewandowski, 2014). The E-CLASS was designed to be given at the beginning and the end of a typical semester, and presents paired questions addressing the students' perception of their own work along with the students' perception of how an expert physicist would view the same. The instrument has been developed and validated through extensive testing and interviews with students participating in 45 classes distributed among 20 different institutions. In order to establish the content validity of an expert view, 23 expert physicists at 7 universities were recruited for the sake of establishing consensus viewpoints of the test items. Most items obtained a 90% or greater consensus, with some items in the 70% or above consensus dealt with instructor beliefs about the difficulty of experimenting and student abilities related to lab methodology. Convergent validity based on correlations with other assessment instruments and course grades has not been obtained; however, student interviews ($N = 42$) conducted for the sake of validation revealed consistent interpretations and valuation of the questions across the curriculum.

Standard lecture courses cause a negative shift in self-efficacy that influences the decline in positive attitudes about Physics and a tendency towards novice theories of Physics, whereas Modeling Instruction—or IE structured courses—produce no change or positive changes to attitudes about Physics in terms of expert-like dispositions (Lindsey et al., 2012; Sawtelle, Brewe, & Kramer, 2010, 2012). IP course designs with epistemological framing in mind obtain conceptual and epistemological gains (Redish & Hammer, 2009) through curricular strategies that promote expert thinking—such as exploring the implications of ideas, sense-making collaborations, and leveraging secure ideas as a sort of conceptual foothold. According to Redish and Hammer (2009, p. 2), students in such a reformed IP classroom learn to coordinate "conceptual and epistemological resources" into their everyday thinking.

The fact that physics is a domain of knowledge requiring rational, empirical, and metaphorical thinking and reasoning (Lancor, 2012; Lee & Chin-Chung, 2012; Plotnitsky, 2012) suggests that epistemological change within this domain involves those same dimensions. The Psycho-epistemological Profile (PEP) described herein was selected for this very reason for deployment on the study sample, as it describes knowledge acquisition in terms of rational epistemologies where knowledge is obtained through reason and logic, empirical dimensions that derive and justify knowledge through direct observation, and a metaphorical dimension where knowledge is derived intuitively with a view to subsequent verification of its universality. Other instruments for measuring personal epistemology—such as the EQ, EBI, and EBS—were not selected due to the fact that after 50 years of international research on personal epistemology, no well-validated instrument capable of measuring epistemological development in large groups of students has emerged (Richardson, 2013). Assuming the PEP dimensions represent mechanisms for epistemological change lends opportunity for consideration of the tools and processes that govern those mechanisms—such as thinking and reasoning with MRS within the context of Physics.

Thinking and reasoning in introductory physics. Instruments such as the FCI and FMCE were designed to measure conceptual change in IP. Findings from assessments such as these are also used to make assertions about the scientific thinking and reasoning of students in IP settings (Cahill et al., 2014; Hake, 1998; Hestenes, 2010) through additional measures such Lawson's CTSR (Coletta & Phillips, 2010)—which is a test of formal reasoning, and the ways in which MRS correspond to the force concept (Nieminen, Savinainen, & Viiri, 2012). In these ways, the PER community is committed to the promotion and assessment of conceptual change through scientific thinking and reasoning with MRS.

Coletta and Phillips (2010, p. 13) created the Thinking in Physics (TIP) instructional program in order to "improve students' thinking and problem-solving skills" in first-semester introductory physics courses. However, though the term *thinking* is used 14 times in the article, nowhere within the article is the term defined; rather, it is always positioned in the context of either scientific reasoning, or problem-solving skills. The conceptual basis for the TIP intervention was the Cognitive Acceleration through Science Education (CASE) program by Adey and Shayer (1994), and the Numerical Relationships (NR) curriculum by Kurtz and Karplus (1979). TIP is one of many IE interventions that enjoys significant gains in conceptual understanding and problem-solving skill (Coletta & Phillips, 2010) when compared to traditional methods of instruction (Hake, 1998). However, no clear definition of thinking and reasoning emerges from this body of literature in spite of the fact that tremendous gains have been recorded by the PER community's attention to theoretical and pedagogical reforms that define IE.

Active learning and IE strategies involving reading, experimentation and discussion produce significant changes in formal reasoning when compared to traditional methods (Marušić, Mišurac Zorica, & Pivac, 2012). In their study, Marušić et al. compared a control group (n =124) experiencing traditional lecture methods, with a group (n = 181) learning physics via lecture and reading (LPLR), and another group (n = 170) learning physics by doing (LPD). Both the LPLR and the LPD groups engaged in discussion of course content, with the only difference being the focus of the discussion being on lecture/reading content versus classroom experiments. There were no statistically significant difference in pretest scores among all three groups, and the control group experienced no significant changes on the post-test event. However, the normalized gain on the CTSR for the LPLR group was 0.016, while the LPD groups had a gain of 0.31. Transitions from concrete thinking to formal thinking amounted to 24% of LPLR learners, and 44% of LPD learners, and was attributed to the active learning strategies of predict, observe, and explain in small and large group settings. In a smaller study, Marusic and Slisko (2012) repeated these findings by obtaining effect sizes of d = 0.30 for the reading, presenting, and questioning (RPQ) group (n = 91), and d = 0.65 for the experimenting and discussion (ED) group (n = 85).

IE is the category under which the most successful reforms in PER fall, and include approaches such as Peer Instruction (Gok, 2011), Modeling Instruction, and Workshop Physics (Cahill et al., 2014), which are all capable of producing conceptual gains of more than twice that of the traditional students on assessments such as the Force Concept Inventory (Bruun & Brewe, 2013; Cahill et al., 2014; Formica, Easley & Spraker, 2010; Rudolph et al., 2014). The Force Concept Inventory (FCI) was created to assess individual students Newtonian force concept before and after instruction, under the premise that said students possess particular scientific reasoning skills (Hestenes, 2010)—even though it never defines the terms: thinking or reasoning.

IE methods alone are not likely to produce the highest conceptual gains on the FCI for portions of the student population who do not possess certain cognitive skills—such as those measured by the Lawson Classroom Test of Scientific Reasoning (CTSR) (Coletta et al., 2007a), or the SAT (Coletta et al., 2007b). Moreover, the companion assessment to the FCI for measuring problem-solving skill associated with the Newtonian concept—the Mechanics Baseline Test (MBT)— further defines the Newtonian threshold in terms of problem-solving ability (Hestenes & Wells, 1992). Students who score 60% or 80% on the FCI are typically able to solve problems on the MBT at the same levels of performance. These findings reveal how conceptual change corresponds to the critical and scientific thinking or reasoning that accompanies problem-solving skill. However, though claiming to have obtained gains in scientific thinking and reasoning through assessments like the FCI and the MBT, the fact that no clear definition of thinking or reasoning has emerged from the PER literature indicates a need to revisit the fundamental underpinnings of the theories and methods that have driven this success. The continued conflation and *fuzzy* or non-existent definitions of the terms thinking and reasoning stalls the scientific progress that is so desperately needed in the research of cognition and instruction. In terms of cognition, the impact of such a renaissance has seemingly limitless potential for clarity and progress within the teaching enterprise.

Representational consistency is the ability to interpret representations of content and context that are isomorphic (Nieminen, Savinainen & Viiri, 2012). In their study of 131 high school students who took the Representational Variant of the Force Concept Inventory (R-FCI) for representational consistency (Nieminen, Savinainen & Viiri, 2010), and the FCI, Nieminen et al. found a strong positive correlation between pre-instructional levels of representational consistency and conceptual change associated with the force concept by correlating pre-test R-FCI scores with FCI gains. Additionally, there was no correlation between pre-instructional representational consistency and the gain that they obtained in representational consistency between pre- and post-test conditions—thus suggesting that prior knowledge is not a limiting factor in a student's ability to learn MRS and subsequently use that new knowledge to advance conceptual change and problem-solving skills (Nieminen et al., 2010). In a related study, De Cock (2012) noted that student success in solving a problem is related to both the representational format of the problem and the underlying concept. Moreover, the ability of a student to deploy MRS is related to the initial representational format of the problem that they are engaged in solving.

The importance of coordinating the psychology of thinking and reasoning with the scientific types and practices of thinking and reasoning converges where conceptual and epistemological changes occur. Multiple Representational Systems (MRS) express the rational, empirical, and metaphorical nature of scientific content (Lancor, 2012; Lee & Chin-Chung, 2012; Plotnitsky, 2012). Human thinking and reasoning, with and on these MRS, is central to the process of science (Plotnitsky, 2012); and therefore to the concepts and beliefs that it has capacity to convey to its consumers.

Study methodology. Hammer and Elby (2012) suggested a qualitative approach to classroom observations of IP student beliefs rather than focusing primarily on the ways that student beliefs differ from educator's views via the use of epistemological surveys. Moreover, careful consideration of the student's epistemological resources as they are situated within the context of IP coursework is central to uncovering the methods and processes that activate them. Bell and Linn (2012) found that students are more likely to develop a collection of disjoint ideas about physics rather than a cohesive view—which requires an effective instructional strategy in order to equip students with the conceptual and representational tools that are need for structuring knowledge in a meaningful way. According to Bell and Linn (2012), one reason for this is that students tend to see science differently than scientific inquiry. In other words, science is merely a static collection of facts, whereas science inquiry is a dynamic knowledge-generating enterprise. Student success is therefore linked to their epistemological view about scientific knowledge.

Learning environments based on IE models have a long-standing record of success in terms of conceptual change related to the central idea in Physics, namely the force concept (see Coletta & Phillips, 2010; Hake, 1998, 2007; Hestenes, 2010). The key features of an IE IP classroom are guide inquiry and collaboration that are facilitated by a pedagogical approach which leverage Socratic dialog as a means for constructing coherent knowledge structures (Cahill et al., 2014; Hake, 1998, 2007; Rudolph et al., 2014). Given the need for student knowledge construction to match the actual process of doing science (Bell & Linn, 2012; Marušić et al., 2012), and the established structure of IE IP learning environments from a modeling perspective (Hestenes, 2010), a qualitative method such as grounded theory (Charmaz, 2006) is required for theoretical advancement in a setting where the lived experience of the students is purposely designed to mimic the true practice of science. Key factors of the learning environment where a proper view of science as inquiry can be developed are ones that position inquiry as a means for obtaining personally relevant understanding, as well as fruitful collaboration and debate of the findings that emerge from inquiry (Bell & Linn, 2012).

Kalman and Rohar (2010) used an intrinsic case study design to determine that a curriculum structured around reflective writing, collaborative groups, and debate is capable of positively influencing the development of a scientific mindset. In their study, Kalman and Rohar recruited over 75 students from three universities in order to collect 3 groups of 5 students—one from each location. The researchers analyzed written artifacts from the case study participants, as well as interview data to assess cognitive activity during reflective writing, summary writing, conceptual change, and views on the usefulness of the course design. In addition to the qualitative evidence for conceptual and epistemological development over the course of one semester, each of 15 participants in this study scored in the top 25% to 75% of their classes on the final examination—thus suggesting a positive outcome for the course design (Kalman & Rohar, 2010).

Hofer (2012) suggested that future research needs to find relations between psychological constructs and epistemological frameworks in order to improve methodology and terminology such that comparable studies can be conducted. Wiser and

Smith (2010) showed how concept formation and personal epistemology are connected through metacognitive control while modeling phenomena; however, conceptual change research has been dominated by pre-post testing strategies (see Hake, 1998) rather than process studies (diSessa, 2010). Representational systems serve as epistemic resources for modeling real-world phenomena (Bing & Redish, 2012; Moore et al., 2013), and it is the coupling of internal representations (mental models) with the external representations that we call models, which is critical to the reasoning process (Nersessian, 2010) and its assessment. These findings suggest a deep connection between personal epistemology and representational systems as they function in concert with thinking, reasoning, and conceptual change. However, it is still unclear exactly what the processes and mechanisms of each construct are (Bendixen, 2012; Hofer, 2012).

The qualitative methodology used in this study—and its associated grounded theory design—are fine-tuned to probe the deep connections described herein between personal epistemology, MRS, and the psychological constructs of thinking and reasoning in terms of conceptual change. Moreover, the evidence that reflective writing and collaboration lead to the development of a scientific mindset (Kalman & Rohar, 2010), as well as an IE instructional setting where classroom activities mimic true science (Bell & Linn, 2012), suggest a research method that has the capacity to reveal the how of processes that influence the lived experience of persons engaged in learning (Bernard & Ryan, 2010; Boeije, 2010) that occurs within in a social environment (Yin, 2011). Qualitative research methods consist of inductive analytical techniques that make developing an understanding of phenomena from the viewpoint of the participants possible (Merriam, 2010) in a manner that respects how the meaning is constructed in social settings (Yin, 2014).

Study instruments and measures. The Hake (1998) study demonstrated conclusively that Interactive Engagement (IE) methods dramatically outperform traditional methods of instruction in terms of conceptual gains as measured by the Force Concept Inventory (FCI) and problem solving skills as assessed by the Mechanics Baseline Test (MBT). A total of 62 Introductory Physics courses with a total enrollment of 6,542 students from various colleges, universities and high schools participated in this study, which found IE methods produced more than double the average gain at nearly 2 standard deviations as traditional methods on the FCI. Results on the MBT involved approximately half the entire study sample (n = 3,259 in 30 courses) showed a strong (r = 0.91) correlation between problem-solving skill on the MBT and conceptual knowledge on the FCI, where the highest gains on the FCI correlated with the highest post-test scores on the MBT. Bothe the FCI and the MBT were fixed events in the normal curriculum of IP students in the study sample at Central Arizona College. While these assessments do not measure epistemological change in any way, they do measure conceptual change—which is expected along the way to epistemological change. Their inclusion in this grounded theory study was based on their place in the natural setting of student experience, as well as their expected value with respect to the theoretical foundations of the study as described herein.

The Psycho-epistemological Profile (PEP) was selected for measuring epistemological change for two reasons. First, the three dimensions that it measures perfectly match the properties of physics as a domain of knowledge requiring rational, empirical, and metaphorical thinking and reasoning (Lancor, 2012; Lee & Chin-Chung, 2012; Plotnitsky, 2012). The PEP defines rational dimension of personal epistemology as knowledge obtained through reason and logic, the empirical dimension of personal epistemology as knowledge derived and justified through direct observation, and a metaphorical dimension where knowledge is derived intuitively with a view to subsequent verification of its universality. Second, the theory and practice of Physics in any setting assumes these dimensions within the varied uses of MRS, and therefore presents an optimal matching of assessment with curriculum and instruction within an IE Introductory Physics course.

Summary

One can hardly deny that thinking and reasoning are fundamental features of the cognitive activities that accompany classroom learning. The evidence described herein suggests a deep connection between personal epistemology, metacognition, and the use of representational systems for the sake of conceptual change (Bendixen, 2012; Mason & Bromme, 2010). However, research initiatives to date have failed to consistently define and distinguish what is meant by the terms thinking and reasoning (Mulnix, 2012; Nimon, 2013; Peters, 2007), as well as the specific factors that produce epistemological change in terms of representational systems, or schemata. One exception to the lack of coherence in defining thinking and reasoning is the multi-decade work of Linda Elder and Richard Paul at the Foundation for Critical Thinking (FCT, 2014). According to Elder and Paul (2007), thinking is merely a form of reasoning—which corresponds to the conflation of both constructs by Mulnix (2012) and Evans (2012). Paul and Elder (2008) then formalized the equivalence of thinking and reasoning by specifying 8 universal elements of thought and 35 dimensions of critical thought. While the model is useful for coding student artifacts, it does not fully assist the effort to answer the research questions that specify thinking and reasoning as separate constructs; hence the author's definitions of (1) thinking as the ability to construct a model, and (2) reasoning is the ability to relate two or models permit a bifurcation of the Paul and Elder model for the sake of analysis.

The two gaps in the literature—mechanisms of epistemological change and thinking versus reasoning—are connected by the representational systems that a student is able to use along with the thinking and reasoning that students employ when solving problems. The central aims of this study are to determine how thinking and reasoning with MRS influences personal epistemological change in an IP classroom.

Introductory Physics students at Central Arizona College participated in a series of activities designed to leverage the power of multiple representational systems for encoding the structure (models) of physical phenomena (law-like behavior), and simultaneously promote metacognitive reflection on the meaning of the results, as well as the tools and the processes that have capacity to produce them. Twenty-nine students comprising 2 class groups served as the study sample. The class groups consist of one algebra-based physics class group and one calculus-based physics class group. The structure of the classroom experience under study matched the conceptual frameworks previously declared for this study in terms of how student journaling and classroom collaboration lead to self-regulated (Cifarelli, Goodson-Espy, & Jeong-Lim, 2010) and self-efficacious (Muis & Franco, 2010) epistemic metacognition (Hofer, 2004). Specifically, collaborative activities shift the locus of control from teacher to student in ways that promote epistemic metacognition (Muis & Duffy, 2013).

The value of this research is rooted in its potential to simultaneously address all of the concerns exposed by the gaps identified within the multiple streams of literature cited herein. In addition to highlighting the deep connections that exist between conceptual change and epistemological change in terms of representational systems, the opportunity to lend clarity to the psychological constructs of thinking and reasoning in general terms as well as how they convey to the central focus of this study (epistemology), is substantial. Representational systems (language in general) are undeniably essential to communicating ideas and personal beliefs within social settings—such as student learning environments. Journaling and collaborative discourse provide ample evidence for how students use and think about the representational systems that they deploy within academic settings. Given the ease with which such artifacts can be obtained, a corpus of student journals, interview and polls are at the core of data collection in study proposed herein. Moreover, as the ebb and flow of classroom activity is somewhat fluid and adaptable to student and instructor needs, a grounded theory design was selected for organizing such data for the sake of the stated research questions.

The research questions for this study can be summarized as: how do students use MRS in their thinking and reasoning about personal beliefs as situated within the context and the goals of an IP course? In other words, how do they think about their beliefs, which are also thoughts *themselves*? Epistemic metacognition (Hofer, 2004) is therefore an almost inevitable outcome within a learning environment where students are required to compare and contrast ideas related to what they think and believe. According to Paul and Elder (2008), thinking and model building of this sort is where scientific opinions and point-of-view emerge. Qualitative methods are ideal for capturing the true nature of participant viewpoints within the natural setting from which they emerge (Bernard & Ryan, 2010; Boeije, 2010) in a social environment (Yin, 2011), and were thus employed by this study.

The qualitative data in the form of student journals, survey, and interviews obtained throughout the study, is punctuated by a number of traditional IE assessments of IP, and the Psycho-epistemological Profile (PEP). The general expectation is that conceptual change as measured by the FCI—or other assessments occurring in the study environment—will correspond with epistemological change as described by the PEP. Given the rich context of IP for the use of MRS, and the seemingly inevitable result of IE methods producing conceptual change (Coletta & Philips, 2010; Hake, 1998), it is reasonable to expect the potential for epistemological change in concert with student discourse and activity within the natural setting of an IP course. Chapter 3 will provide a detailed accounting of student views and practice using MRS in Physics.

Chapter 3: Methodology

Introduction

The purpose of this study is to determine how students in an IP classroom think and reason with MRS as they experience epistemological change. The importance of this study hinges on its ability to answer a long-standing deficit in the literature on epistemological change (Bendixen, 2012; Pintrich, 2012) by providing a deeper understanding of the processes and mechanisms of epistemological change as they pertain to context (domain of knowledge) and representational systems in terms of the psychological constructs of thinking and reasoning. Such findings better inform the Physics Education Research (PER) community concerning the capacity that MRS have for encoding meaning during the scientific thinking and reasoning process, while simultaneously clarifying what is meant by those processes. Moreover, the relative importance of personal epistemology in the process of conceptual change—either as a barrier or a promoter—is the kind of information needed for continued progress in the PER reform effort, as well as learning theory in general. The importance of advancing scientific thinking and reasoning, conceptual change—in terms of epistemological change—lies in the clear evidence from PER that conceptual change has a positive effect on achievement in terms of problem-solving skills (Coletta & Phillips, 2010; Coletta et al., 2007a; Hake, 2007).

The research questions can be summarized as how do students in IP use representational systems to encode meaning, and promote their own thinking, reasoning, and understanding, as they experience conceptual and/or epistemological change? This chapter presents a detailed review of the research questions and the methodology and design employed to answer them. Efforts to ensure the validity and reliability of the measures and instrumentations are discussed in conjunction with the data collection and analyses. The chapter terminates with a discussion of ethical concerns and various limitations of the study.

Statement of the Problem

It was not known how (a) thinking and reasoning with multiple representational systems (MRS) occurs, and (b) how that sort of thinking and reasoning affects epistemological change in terms of mechanisms and processes—whether cognitive, behavioral, or social—in an IP classroom. The use of representational systems—such as symbols, diagrams, and narratives—is undoubtedly central to the progress of science education by virtue of its ubiquitous deployment in the realm of natural science itself (Plotnitsky, 2012). Given the *cognitive filter* that personal epistemology provides for the acquisition and the application of knowledge (Schommer-Aikins, 2012), it seemed reasonable to investigate the nature of epistemological change in concert with the thinking and reasoning that occurs by means of the representational systems associated with a domain of knowledge—such as IP.

The importance of this study hinged on its ability to answer a long-standing deficit in the literature on epistemological change (Bendixen, 2012; Pintrich, 2012) by providing a deeper understanding of the processes and mechanisms of epistemological change as they pertain to context (domain of knowledge) and representational systems in terms of the psychological constructs of thinking and reasoning in an IP classroom? Such findings would then better inform the Physics Education Research (PER) community concerning the capacity that MRS have for encoding meaning during the scientific thinking and reasoning process, while simultaneously clarifying what is meant by those processes. Moreover, the relative importance of personal epistemology in the process of conceptual change (diSessa, 2010)—either as a barrier or a promoter—is the kind of information needed for continued progress in the PER reform effort (Redish, 2013), as well as learning theory in general.

Research Questions

The goal of this qualitative grounded theory study was to determine the influence that multiple representational systems (MRS) have on the thinking and reasoning of community college students with respect to their conceptual frameworks and personal epistemology. Semi-structured interviews based on instructional goals, survey response data, and student journal entries were conducted at regular intervals during the study in order to obtain emergent themes concerning how students think and reason about mathematics, as well as how they monitor their own thinking. Journals and semi-structured interviews—in the form of group Socratic dialogs—revealed the ways in which students shift between representational systems (*languages*) in an effort to model mathematical systems. Multiple electronic polls were given throughout the treatment in order to capture opinions about thinking and reasoning, knowledge acquisition and usage, as well as how concepts and beliefs change as a result. Exit interview questions terminated the semester filled with daily group interview/discussions and several weekly journals covering the same material. By that time, the study populations ability to have substantial and meaningful discourse was fairly well developed, as evidenced by the more than 200 pages of interview transcripts. Also, each individual submitted a written version of his or her own answers to the exit interview questions prior to the interview.

R_1: How do IP students use MRS in their thinking and reasoning?

R_2: How does the use of MRS in the thinking and reasoning of IP students promote personal epistemological change?

The instrument used herein for assessing personal epistemology (the PEP) has no preferred direction for epistemological change because it simply measures personal epistemology along three dimensions: rational, metaphorical, and empirical. The structure of an IP course is already fine-tuned to the PEP dimensions given the widespread use of MRS in a collaborative learning community focused on conceptual development and problem-solving skills that involve the use of narrative, specialized symbol systems, and diagrammatic tools. The PEP survey was selected primarily due to its affinity with an IE IP course as described above; but also in light of the fact that the most-used instruments for personal epistemology still suffer from unstable factors (Barzilai & Zohar, 2014).

A grounded theory approach (Charmaz, 2006) was used in designing this qualitative study in order to produce a substantive theory capable of describing the complex interactions that comprise the phenomena of thinking and reasoning with MRS, and its influence on epistemological change within the context of a community college IP classroom. Grounded theory is a qualitative design that allows a researcher to form an abstract theory of processes or interactions that are *grounded* in the views of the participants (Charmaz, 2006; Glaser & Strauss, 2009). Given the fact that personal epistemology is entirely about personal beliefs and viewpoints, a grounded theory exploration of the underlying mechanisms and processes of epistemological change is entirely consistent with the research questions probing *how* students think and reason their way towards epistemological change using MRS. Thirty-four students comprised the study population from which the archived data on 29 of those students was drawn—which is consistent with the 20-30 study participants recommended for grounded theory research by Creswell (2013), and the 30-50 participants suggested by Morse (2000). Charmaz (2006) suggests that 25 interviews is sufficient from grounded theory designs on small projects, and this study consisted of 44 interviews. Given that the study used interviews, written journals, and electronic polls, a group of 29 student participants was more than adequate in order to obtain the level of theoretical saturation which is the ultimate criterion for sample size in grounded theory designs (Corbin & Strauss, 2008).

Research Methodology

A qualitative approach was used in this study. The foundations of qualitative research rest on the inductive analysis that makes developing an understanding of the phenomena from the viewpoint of the participants possible (Merriam, 2010) in a manner that respects how the meaning is constructed in social settings (Yin, 2014) where the researcher is the primary data collection *instrument* responsible for producing a richly descriptive account of the outcomes (Merriam, 2010). Given the nature of the study on personal epistemology—beliefs about knowledge and its acquisition—and how students obtain advances in personal epistemology, qualitative methods lend themselves best to the project described herein because quantitative test scores do not address the 'how' of anything with a view to theory building until qualitative methods expose the concepts and hypotheses to be quantified (Yin, 2011). Moreover, given that the research design was grounded theory, the necessity of qualitative methodology for data collection and analysis is properly constrained within this methodology by virtue of its underlying logic and interpretive framework (Charmaz, 2006).

Research Design

A grounded theory approach (Charmaz, 2006) was used in designing this qualitative study in order to advance a new theory that is capable of describing the connections that exist between thinking and reasoning with MRS, and its influence on epistemological change relative to the student experience in an IE IP classroom. Grounded theory designs lend a researcher the required tools for developing a theory of processes or interactions that are *grounded* in the views of the participants (Charmaz, 2006; Glaser & Strauss, 2009). Personal epistemology is entirely about personal beliefs and viewpoints; therefore, a grounded theory exploration of the underlying mechanisms and processes of epistemological change is entirely consistent with the research questions probing *how* students think and reason their way towards epistemological change using MRS.

Baxter Magolda (2004) deployed a grounded theory approach for a 16-year longitudinal study upon which the Epistemological Reflection model (Baxter Magolda, 2012) was established, because of its affinity with constructivist developmental theories, the constructivist paradigm in general, and the fundamental structure of qualitative inquiry at large. According to Baxter Magolda (2004), the data that she obtained from more than 1,000 students prior to the longitudinal study served as the categories against which the grounded theory could be constantly compared to the evolving interpretations that emerged throughout the study period. In this way, the grounded theory defines the core category around which all emergent themes find ground (Corbin & Strauss, 2008), and thus serves to manage the uncertainty—and even the bias—that accompanies the analysis of personal epistemology as observed within a constructivist context.

Palmer and Marra (2004) used a grounded theory design to study the domain-specific epistemologies of 220 students attending a large eastern research university. Students were interviewed extensively in order to determine their epistemological orientation of science as facts versus humanities as facts (stage 1), science as theory versus humanities as opinions (stage 2), and science as an evolving construction of commitments within theory versus humanities as construction of facts with evidence and reason (stage 3). In a sub-sample of 60 upper division students in science and engineering, it was found that the shift from stage 1 to stage 2 is easier for the humanities student than it is for the science student; however, the shift from stage 2 to 3 is much easier for the science student than the humanities student. The grounded theory design selected by these researchers allowed for the evidence to be grounded in the narratives of the students engaged in epistemic development, and thus form a predictive theory for explaining the differences and the transitions that naturally emerge.

Thirty-four Introductory Physics (IP) students comprised the study population from which archived data on 29 of those students was sampled—which is consistent with the 20-30 study participants recommended for grounded theory research by Creswell (2013), and the 30-50 participants suggested by Morse (2000). Charmaz (2006) suggested that 25 interviews are sufficient from grounded theory designs on small projects, and this study conducted 44 interviews. A similar study consisting of 18 students used interviews and questionnaires to compare and contrast domain-specific epistemological beliefs with respect to physics and biology (Lee & Chin-Chung, 2012). Forsyth (2012) conducted a single case study of one individual examining the epistemology of far transfer—how one domain of knowledge influences understanding other domains—using a series of three interviews aimed at describing the relations of similarity between physics and its application to other content areas. Given the current study is using interviews, written journals, and electronic polls, a group of 20 – 30 student participants should be more than adequate for obtaining the level of theoretical saturation which is the ultimate criterion for sample size in grounded theory designs (Corbin & Strauss, 2008).

Population and Sample Selection

Thirty-four students enrolled in two IP courses at Central Arizona College— a Hispanic serving institution (HSACU, 2014) located in Coolidge, Arizona—during the 2014 fall semester, comprise a small portion of the nearly 6,500 students attending that campus. Course enrollment in each course was 17 students ranging in age from 17 - 45. Archival data collected on the study sample of 29 students was from the existing curriculum for IP students at Central Arizona College. Site authorization (see Appendix B) has been obtained to use archived data, and specifies how the school and the researcher will maintain anonymity of the student study sample during data collection and analysis. Given that the data collected was from archival sources, no informed consent was required or obtained. Yin (2011) stated that Institutional Review Board (IRB) practices are typically ambivalent when it comes to data sources such as these; however, so long as the basic ethical mandate to protect the anonymity of students is upheld, archival data in this form does not require consent. Nevertheless, the growing trend within social science research to use textual and visual archived data is an ethical problem only to the extent that as databases increase in size, the chances of identifying participants becomes more likely (Crow & Edwards, 2012). Given that the archival database for this study is limited to one college with participants who spend no longer than 2 years at the institution, the threat of violating anonymity is virtually non-existent so long as local researchers and the local IRB maintain data security. Moreover, the decision to use archived data—i.e. artifacts already graded and returned to students of the researcher—was implemented so that students felt no undue performance pressure relative to the study. Artifacts collected during the progress of each course contain no student identifiers other than their student identification number, which is removed prior to release for analysis through a joint effort of the local IRB office and the author-researcher, and replaced with generic identifiers FS1 and MS1 in order to designate female student 1, and male student 1, respectively. Archived data will be held on site by the author-researcher for no more than 5 years prior to disposal.

The study population from which archived data will be drawn consisted of 34 individuals—which is consistent with the 20-30 study participants recommended for grounded theory research by Creswell (2013), and the 30-50 participants suggested by Morse (2000). This study conducted 44 semi-structured interviews, which is far more than the minimum 25 suggested by Charmaz (2006) when using grounded theory designs on small projects. Given the current study is using interviews, written journals, and electronic polls given within the online learning management system used for coursework, a group of slightly 29 student participants should be more than adequate for obtaining the level of theoretical saturation which is the ultimate criterion for sample size in grounded theory designs (Corbin & Strauss, 2008).

Instrumentation and Sources of Data

The IP course from which archived data were sampled involves semi-structured interviews in the form of group discussions following lab investigations, electronic polls, group interviews, and student journal entries that are collected throughout the semester. During the first part of the course under study, topics including the nature of physics and reality, as well as the foundations of mathematics and geometry were part of the curriculum leading into the enterprise of crafting physical laws that describe empirically familiar regularities in nature. The terminal point of the course is group exit interviews; however, its content is contingent on progress through the activities that precede it, and most likely not in the treatment phase. The following diagram illustrates the typical flow of activities during each of learning cycle. Each student will complete the Psycho-epistemological Profile (PEP; Royce & Mos, 1980) before any IP class activities are conducted, and then again prior to the end of the course. Each participant will complete the study by participating in a group exit interview that includes a review of the changes in their PEP profile scores.

The Psycho-epistemological Profile (PEP) measures personal epistemology on three dimensions: Rational, Empirical, and Metaphorical (Royce & Mos, 1980). The rational dimension of PEP assumes that knowledge is obtained through reason and logic, whereas the empirical dimension derives and justifies knowledge through direct observation. The metaphorical dimension of PEP *sees* knowledge as derived intuitively with a view to subsequent verification of its universality.

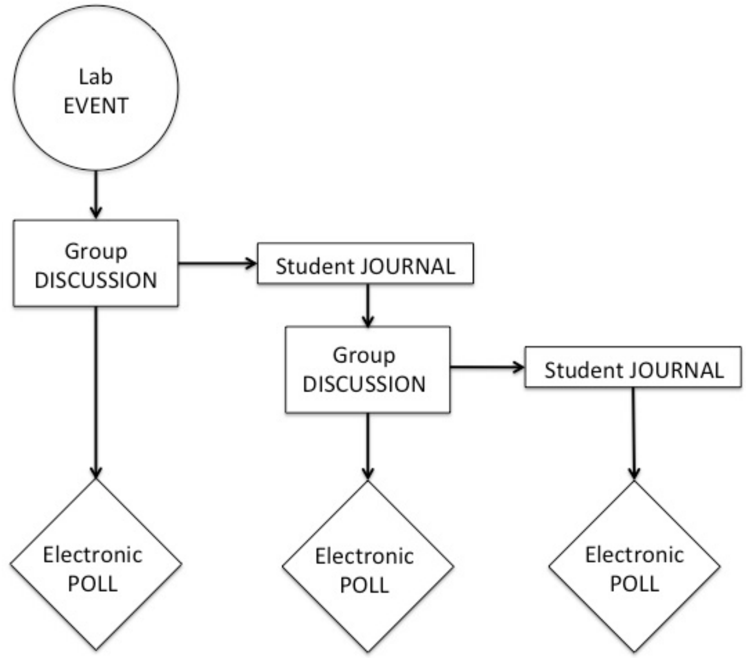

Figure 3. Typical classroom activity life cycle.
In general, the standard curriculum for IP students at CAC involves a guided inquiry (lab) event followed by 1 - 2 group collaborations and discussions, as well as subsequent electronic polling. At least one individual journal assignment is included along with a follow-up writing assignment.

Classroom activities and assessment instrument. Four distinct classroom activities comprised the standard curriculum at the beginning of each IP class delivered at Central Arizona College, which address the nature of Physics versus reality, the conceptual basis of numbers, how to physically model a conversion factor, and creating physical laws of motion from basic observations. Each activity is described in detail below, as well as included in Appendices A-G.

Physics and reality. The very first activity of this study existed to set up the basic nature of classroom discourse as a Socratic dialog within a learning environment designed to mimic a scientific community—otherwise known as Modeling Discourse (Hestenes, 2010). Students began by individually answering the following questions in writing. What is Physics? What is Reality? Is Physics Reality? Students then form small groups of 3-4 and compare their answers with a goal to report some sort of consensus to the larger group. During the larger group discussions, each student team presented their findings on small whiteboards during what is henceforth called a "board meeting." The instructor/evaluator posed a series of questions addressing the how and the why that students answered the way that they did in an open-ended semi-structured group interview.

As a follow up to this activity, students were assigned a Library/Internet research project to investigate other opinions/beliefs about this series of questions, and summarize those findings in a short essay where they reflect on their own initial set of beliefs, and compare it to both the small and large group consensus, as well as their new findings from the research project. A poll addressing the change in belief and the mechanisms for that change was crafted based on these results was delivered prior to the post-essay follow up discussion through the learning management system used for all coursework. A second semi-structured group interview addressing the student data generated thus far in the study asked students to reflect on how and why their beliefs have or have not changed as a result of the activity. Additionally, students were asked how they felt about the process, and how this may have changed their views about science in general.

Numbers do not add. The second activity was step one in delivering new and modified mathematical representational systems for use throughout the course, and was designed to produce a conceptual change about what numbers actually are, and what they are used for in mathematical modeling. The worksheet provided to each small group of 3-4 students consisted of modifying a circle and a square to the point where each shape has been partitioned into fourths, and labeled with the appropriate numeral ¼. Students were then compelled to join each representation—the geometric and the numeric—by addition. This step presented a new challenge to students because their normal belief that ¼ + ¼ adds up to ½ is challenged by the fact that joining the circle and square into one new hole includes shaded regions that are still ¼ of the new whole. The activity transitioned into students crafting a consensus viewpoint about what has just happened suitable for sharing with the full class group. The central goals of the activity were to challenge the traditional concept of number that student presently hold, as well as the arithmetic representation and operational definition of the fraction/quotient operation. The instructor posed a series of questions addressing the how and the why that students answered the way that they did.

The follow up individual journal assignment (one-page or more essay) required each student to reflect on what he or she learned and how their understanding of number, fraction and quotient—and the ways that they are represented—had changed as a result of the activity. A poll addressing the change in belief and the mechanisms for that change was be crafted based on these results, and delivered prior to the post-essay follow up discussion through the learning management system used for all coursework. A second semi-structured group interview addressing the student data generated thus far in the study asked students to reflect on how and why their beliefs have or have not changed as a result of the activity. Additionally, students were asked how they feel about the process, and how this may have changed their views about science in general. This activity was one of many activities described herein designed to change thinking and reasoning, and thus personal epistemology as beliefs and concepts change as a result of such influences.

The law of the circle. This activity leveraged the findings of the prior activity as step two in learning how to build mathematical (axiomatic) laws from basic observations (measurement) first represented in natural language (narratives). Students were given a set of different sized tubes and equipment for measuring circumference and diameter. The goal was to not only obtain the measurement data, but also to recognize the empirically familiar regularity that circumference and diameter increase or decrease together, which served as the basis for stating a physical law about circles. Subsequent to obtaining a suitable version of this law in natural language form (determined by instructor/evaluator), and based on an expanded view of what a quotient operation can be used for from the prior experiment, students were guided through the process of using arithmetic to craft the conventional formula for the circumference of a circle. The instructional goal had been reached at the point where students recognize that the relationship between circumference and diameter is always the same—i.e. the number pi. In the large group discussion that followed, the instructor posed a series of questions addressing the how and the why each student group answered the way that they did, as well as how the feel about their changes in thinking and reasoning.

The follow up individual journal assignment (one-page or more essay) required each student to reflect on what he or she learned during the activity, and how their understanding of number, fraction, quotient, and equation—and the ways that they are represented—has changed as a result of the activity. A poll addressing the change in belief and the mechanisms for that change was crafted based on these results, and delivered prior to the post-essay follow up discussion through the learning management system used for all coursework. A second semi-structured group interview addressing the student data generated thus far in the study, asked students to reflect on how and why their beliefs have or have not changed as a result of the activity.

The zeroth laws of motion. Based on observations of various aspects of simple motion—such as dropping and/or rolling a ball—students were guided to a conclusion consistent with the fact that no object can be in two places at the same time, or that it always takes some non-zero amount of time in order for anything to change position. There were numerous variants on those statements, and the goal was to simply get as close as possible to either of the two model statements provided herein. This inquiry leveraged the findings and skills developed in the two prior investigations in terms of how to encode empirically familiar regularities (laws) using symbols and arithmetic operations—namely the quotient operation in terms of how it has come to be defined in the study. The traditional instructional goal of this activity was to obtain the essence of the principles of momentum and energy—upon which all of physics is based, and are more fully explicated as the course progressed beyond the study phase.

The follow up individual journal assignment (one-page or more essay) required each student to reflect on what he or she learned during the activity, and how their understanding of momentum, energy, laws, and physics—and the ways that they are represented—had changed as a result of the activity. A poll addressing the change in belief and the mechanisms for that change was crafted based on these results, and delivered prior to the post-essay follow up discussion through the learning management system used for all coursework. A second semi-structured group interview addressing the student data generated thus far in the study, asked students to reflect on how and why their beliefs have or have not changed as a result of the activity.

Exit interviews. Each study participant completed a brief semi-structured group interview designed to elicit responses that represent their reactions and feelings about the entire experience. Within the structure of those small-group interviews, the following questions were directed at each participant. Each interview was recorded and subsequently transcribed for analysis. The following questions are based on the two research questions described in chapter 1: (R_1) How do IP students use representational systems in their thinking and reasoning, and (R_2:) How does the use of MRS in the thinking and reasoning of IP students promote personal epistemological change? This body of questions served as a foundation for a semi-structured discussion designed to elicit extensive student response concerning their own thinking and reasoning relative to personal epistemology.

1. How has your thinking changed as a result of this experience?
2. How has your reasoning changed as a result of this experience?
3. How has your understanding changed as a result of this experience?
4. Do any of these changes impact your thinking and reasoning outside of this experience? How so?
5. Do any of the changes in your understanding impact your beliefs about anything? How so?
6. In what ways have any personal beliefs changed as a result of this experience?
7. How would you describe conceptual change, and have you experienced any during this experience?
8. What conceptual changes have you identified in yourself?

Validity

Validity can be obtained through triangulation, saturation, data trails, bracketing the researchers' subjectivity/bias, member checks and participant review, prolonged engagement, and reflexivity (Frost, 2011), as well as simply giving attention to disconfirming evidence and contradictory interpretations—which is essential to establishing the *trustworthiness*, or validity of qualitative data (Yin, 2011). Saturation is a state within qualitative analysis where new data is no longer productive in its capacity to generate new themes or categories, and is therefore contingent on the efficiency of the data collection and management processes that precede it. Properly coding the data, summarizing, and aggregating those results is not only essential to obtaining confidence in the emergent themes, but also the only way to really know that you have reached a saturation point (Saldaña, 2013). Triangulation through multiple data sources—interviews, documents, and field notes—generally serves the needs of validity for the qualitative aspects of this study.

The data sources for this study included field notes and memos from the author-researcher observations, written journal documents, transcribed group interviews, small group lab discussions, data journal entries, and conceptual inventory results from instruments like the FCI and TUG-K. Journal, interviews and field notes/memos were sufficient for triangulation in this study. Two coding schemes—a priori theoretical and indigenous in vivo—were deployed in this study. The theoretical codes—such as instances of thinking or reasoning with one or more representational systems—flowed directly from the research questions, and the definitions for the constructs of thinking and reasoning that the author-researcher had derived from the literature. Indigenous (in vivo) codes were derived directly from the data as it was analyzed, and was therefore unpredictable in many ways; however, given the nature of this study, it was reasonable to expect changes in belief and concept, as well as opinions about the usefulness of various facts and the authority they carried. Given the nature of the study and the metaphorical dimension of personal epistemology on the PEP survey, the coding for narrative mechanisms such as metaphors/analogies was expected. The data sources described herein involved small group, large group, and individual contributions for each activity under study in the form of written documents, group narratives, and polling data; and therefore provided a complete and complementary picture of student beliefs, as well as the ways in which they come to those beliefs. Both coding schemes were applied to all three data sources providing a coherent way to triangulate the data.

Reliability

The concept of reliability in qualitative research is identical to quantitative methods, in that (a) consistency is the goal, for the sake of (b) replication by other researchers (Butler-Kisber, 2010). Qualitative research is capable of generating millions of words that must be grouped into "units of work" that subsequently can be coded semi-quantitatively (Johnson, Dunlap, & Benoit, 2010). While each student and group may respond differently to a particular treatment, it is the nature of the activities and the questions therein that must be consistent in order for replication of the study to be meaningful. The details of classroom activity provided in a prior section were given with this end in mind. With respect to the study itself, those classroom activities were designed to correspond to one another progressively, while also retaining the same structure in terms of individual, small-group, and large-group activities, both in scope and in sequence.

There are at least two levels of replication that researchers attempting to repeat this study should be aware before starting a similar study. First, though the content of IP is extremely stable, the classroom and its curriculum are reformed in accordance with the Interactive Engagement (IE) methods and paradigms described in the literature review; thus requiring some minimal preparation in those techniques in order to *match* the overall framework of this study. Second, the PEP instrument, and the various PER community assessments such as the FCI, make no assumptions about the structure and pedagogy of the learning habitat. Any IP class is eligible to use these same assessment devices for their intended purposes. Finally, the nature of the student body is a minor factor in terms of developmental trajectories and demographic qualities. The setting was a rural community college serving a largely Hispanic population student body with ages ranging from 16 – 63 for the college at large, 17 – 45 within the study population, and 18 – 45 within the study sample.

A remaining threat to reliability is researcher bias; however, field notes and memos served as two methods of bracketing the personal bias of the author-researcher during data collection and analysis (Butler-Kisber, 2010). The methodological elements of triangulation that lend validity, actually provided the basic structure for reliability as it pertains to (1) variations in observation and (2) data collection techniques (Butler-Kisber, 2010).

Data Collection and Management

Site authorization to use archived data from the IP course under study was obtained (see Appendix C). The student groups participating in this study were a purposive sample (Bazeley & Jackson, 2013; Frost, 2011) of adult community college students at Central Arizona College. Thirty-four students comprised the group that met twice weekly for 3-hour sessions where group interviews and lab activities were conducted, and were separated by electronic polls, traditional homework assignments, and journal artifacts collected through the course management system. Electronic polls were administered as a follow-up to group interviews and journal assignments that are coordinated with classroom events. Poll results were subsequently the focus of journal reflections about personal and corporate classroom views. The audio of interviews and classroom collaborations were recorded, and subsequently transcribed and analyzed. Student anonymity was maintained through the use of generic ID numbers during the collection of survey instruments—including, but not limited to: the Force Concept Inventory (FCI), the Mechanics Baseline Test (MBT), the Psycho-epistemological Profile (PEP), and the Test of Understanding Kinematics Graphs (TUG-K), which are normal events within the lifecycle of IP courses at Central Arizona College. Given that the data collected was from archival sources, no informed consent was required or obtained.

The FCI is a multiple-choice assessment designed to be given in a pre-test and post-test sequence surrounding a first-semester physics course. FCI results are meaningful when the Hake (1988) gain is calculated for each student and the class as a whole. The MBT is designed to be given as a single-event test near the end of a course, and has the features of serving as a standard exam, as well as being well coordinated with FCI. The TUG-K is a standalone test that can be given as a pre-post-test if desired, so long as the pre-test comes before curriculum content exposure to graphing kinematics. Finally, the PEP survey is also a pre-test/post-test survey that should encompass the treatment designed to produce epistemological change. All of these instruments are paper-and-pencil multiple-choice tests delivered in the classroom environment of the study sample. Scan forms are graded using the ZipGrade© app on an iPad, and then transferred to a spreadsheet for analysis and subsequent import to SPSS.

The vast majority of data collected comes in the form of journal assignments (essays) embedded throughout the standard IP curriculum at Central Arizona College. Journal assignments direct the students to reflect on their own thinking in terms of how concepts and beliefs have changed, and what in their opinion was the source of those changes, if any. A number of group interviews have been recorded that punctuate these journal assignments, and serve to represent a *group-think-aloud* with the expectation that its influence can be seen in subsequent personal journal entries. A number of electronic and paper-based polls were also given in order to obtain rank-orderings of various representations and the reflections on why one is preferred over the others. The ordinal polling data arising naturally within the curriculum leads to basic descriptive statistics, which serve merely as a backdrop to the qualitative analysis of this study. Each of these general approaches to data collection served the interests of the research questions that seek to describe how students think and reason with MRS along the way to personal epistemological change.

The Institutional Review Board (IRB) Office at Central Arizona College will worked in concert with the author-researcher in order to collect all course artifacts prior to release for analysis. All student identifiers present on written documents and assessments were removed and replaced by generic identifiers—such as Student 1, Student 2, etc.—for the sake of anonymity. Transcripts of group interviews recorded in the classroom were obtained via the TranscribeMe ™ service embedded within the NVivo software used in this study for qualitative analysis. All data collected will remain on site with the author researcher for no more than 2 years prior to being disposed of through shredding of paper artifacts and deletion of electronic files.

Data Analysis Procedures

The student groups participating in this study were a purposive sample (Frost, 2011) of adult community college students at Central Arizona College. Thirty-four students were in the group that met twice weekly for 3-hour sessions where group interviews and lab activities were conducted, and were separated by electronic polls, traditional homework assignments, and journal artifacts collected through the course management system. Electronic polls are administered as a follow-up to group interviews and journal assignments that are coordinated with classroom events. Poll results are subsequently the focus of journal reflections about personal and corporate classroom views. The audio of interviews and classroom collaborations are recorded, and subsequently transcribed and analyzed.

Preparation of data. The Institutional Review Board (IRB) Office at Central Arizona College worked in concert with the instructor to collect all course artifacts prior to release for analysis. All student identifiers present on written documents and assessments were removed and replaced by generic identifiers—such as Student 1, Student 2, etc.—for the sake of anonymity. Transcripts of recorded interviews were obtained via the TranscribeMe ™ service embedded within the NVivo software used in this study for qualitative analysis. Coding in Nvivo will correspond to the theoretical aspects of the research questions—such as instances of encoding that are representative of thinking, reasoning, conceptual and/or epistemological change—as well as emergent themes occurring naturally during document and narrative analysis (Butler-Kisber, 2010; Rubin & Rubin, 2012).

Data analysis. The first step of data analysis is open coding for the identification of key words and word groupings in the data (Saldaña, 2013). Step two of data analysis follows with in vivo codes when important words and word groupings warrant their own code label. Groups of related codes form categories that can become theoretically saturated when new data analysis returns the same codes (Birks & Mills, 2011). Constant comparison of current activities to prior activities, researcher memos on the current and prior activities, group interview transcripts, and emergent themes and patterns in all of the artifacts produced by the study population were coded within Nvivo in an effort to reach saturation. NVivo codes were analyzed for relationships and subsequently displayed in multiple graph formats ranging from bar charts to cluster analysis maps that reveal the relationships that exist between nodes (codes) and/or families of nodes (Bazeley & Jackson, 2013).

Two coding schemes—a priori theoretical and indigenous in vivo—were employed in this study. The theoretical codes flowed directly from the research questions, and the definitions for the constructs of thinking and reasoning that the author-researcher had derived from the literature based on the EOT by Paul and Elder (2008). Per the research questions concerned with the constructs of thinking and reasoning with MRS for epistemological change, four basic theoretical codes were used in order to begin the coding process: thinking, reasoning, representation, and epistemology/epistemological—which are the key elements of the two research questions that ask how students think and reason with MRS and how that corresponds to epistemological change. Thinking can be defined and detected as critical or scientific, whereas reasoning can be defined and detected as metaphorical, analogical, or proportional. Representational systems come in multiple forms such as spoken or narrative language, diagrammatical, graphical, and symbolic.

Indigenous (in vivo) codes flowed directly from the data as it is experienced or analyzed, and are therefore unpredictable in many ways. There was little need for memos on the theoretical codes as they are constructed a priori; however, in vivo coding required a nearly constant practice of writing memos concerning not only the basis for creating a new code (Birks & Mills, 2011; Saldaña, 2013), but also how to bracket the researchers bias relative to the observations and expectations of the researcher. In conjunction with the epistemological change detected between pre-post-test conditions of the PEP, each source of data—interviews, journals, and polls—proved to be a rich framework from which to analyze how students think and reason with MRS in concert with personal epistemological change.

Themes emerged in two ways. First, the researcher perceived a theme, and second that theme was confirmed or denied by the pattern that can be *seen* when a large enough family of nodes encodes for a trait or construct evident in the data (Bazeley & Jackson, 2013). Visual analysis in NVivo provided for the coordination of many different codes such that a correspondence between theoretical and/or in vivo *themes* was evident by inspection of cluster analysis, and frequency charts.

Ethical Considerations

No personal or acute affects were expected for any persons in the study population drawn from archived data. An IRB representative from Central Arizona

College's Office of Institutional Planning and Research verified that no student identifiers were present in the sampled data. In an effort to assist in maintaining anonymity for various assessment and research purposes, much of the archived data is already free of names and other student identifiers, as well as the fact that electronic polls were completed anonymously. All student identifiers present on written documents and assessments will be removed and replaced by generic identifiers—such as Male Student 1, Female Student 2, etc.—for the sake of anonymity. Students also used avatar names on each document submission—which further protected student anonymity without researcher oversight. The potential for student coercion has been eliminated by the fact that any students' grades associated with the archived data were already finalized prior to collection and analysis. Artifacts collected during the progress of each course contained no student identifiers other than their student identification number and/or avatar name. Archived data will be held on site in a locked room by the researcher for no more than 5 years prior to disposal so that other researchers can access the data. Researcher bias was handled by bracketing the presuppositions of the author throughout the phases of data collection and analysis (Fischer, 2009).

Limitations and Delimitations

Many of the limitations with research methodology arise when only one method is used (Frost, 2011). A grounded theory design has methodological capacity for deploying multiple methods, such as ethnographic and phenomenological (Charmaz, 2006), and is therefore able to leverage those combined strengths while minimizing individual methodological weaknesses. The bricolage of multiple methods in such a design allows the multiple perspectives that come with those analytical approaches to minimize the assumptions of researcher bias (Frost, 2011) while simultaneously increasing the reliability and validity of the findings (Butler-Kisber, 2010). Qualitative research has general limitations of researcher skill, time required for deep analysis, researcher bias, researcher presence, and limits to generalizability.

Given the stability of all assessment instruments used in this study, as well as the acceptance of grounded theory and qualitative methods for social science research, the limitations of the study were primarily limited to (1) the researchers personal bias, and (2) the reformed pedagogy and curriculum that is described in the PER literature detailed within the literature review. Researcher bias was handled by data collection protocols such as memos during both data collection and data analysis, which bracket the presuppositions and opinions of the researcher relative to the observations that they make, and the inferences that they draw from the data. The reformed pedagogy common to IP classroom using IE methods has a strong theoretical and empirical foundation that has been already been described in the literature review, and therefore presented no challenge to authenticity pertaining to content and practice. However, replicating some of the curriculum content in the absence of training in IE methods for IP is likely to affect the receipt of similar effects using the same line of question and assessment. Technically, this is not really a limitation at all, as one would expect different teaching styles and curricular content to have different affects with students.

Summary

The purpose of this qualitative study was to determine the influence that multiple representational systems (MRS) have on the thinking and reasoning of community college students with respect to their conceptual frameworks and personal epistemology.

The importance of this study hinged on its ability to answer a long-standing deficit in the literature on epistemological change (Bendixen, 2012; Pintrich, 2012) by providing a deeper understanding of the processes and mechanisms of epistemological change as they pertain to context (domain of knowledge) and representational systems in terms of the psychological constructs of thinking and reasoning. A grounded theory approach (Charmaz, 2006) was used in designing this qualitative study in order to produce a substantive theory capable of describing the complex interactions that comprise the phenomena of thinking and reasoning with MRS, and its influence on epistemological change within the context of a community college IP classroom.

Thirty-four students enrolled in two IP courses at Central Arizona College— a Hispanic serving institution (HSACU, 2014) located in Coolidge, Arizona—during the 2014 fall semester, comprise a small portion of the nearly 6,500 students attending that campus. Course enrollment in each course was 17 students ranging in age from 18 - 45, including one 17-year-old male not included in the study. Archival data collected on 29 students comprising the study sample was from the existing curriculum for IP students at Central Arizona College. The IP courses from which archived data was sampled involved semi-structured interviews in the form of group discussions following lab investigations, electronic surveys, and student journal entries that were collected throughout the semester.

The expectation of this study was the finding that multiple representational systems (MRS) are factors of epistemological and conceptual change. Moreover, the qualitative findings of student discourse and document analysis revealed how MRS facilitates thinking and reasoning according to the operational definitions provided herein. Given that this qualitative study aimed simply to explore the data, a hypothesis about the number and type of representational systems and their capacity to produce conceptual and epistemological change emerged from the findings, and thereby served the needs of further theoretical development. The analytic basis for the development of new theory from this study began with the coding process, with open coding of key terms—such as thinking and reasoning.

Journal activities—and the discussions that punctuated them—generated self-efficacy and self-regulated learning through metacognitive monitoring (Muis & Franco, 2010), while simultaneously providing a rich source of evidence for student thinking and reasoning. These same data also revealed connections between conceptual and epistemological change through what Hofer (2004) described as epistemic metacognition. The model for scientific thought advanced by Elder and Paul (2007b) corresponded with the advance of self-efficacy and self-regulation that is consistent with epistemic change in scientific domains of knowledge (Mason et al., 2012; Sawtelle et al., 2012).

Following the data analysis in this chapter, the researcher leveraged the qualitative results of this grounded theory study in the form of a new theory concerning the nature of thinking and reasoning with multiple representational systems (MRS) and how that corresponds to personal epistemological change in terms of conceptual frameworks. Summaries of the content analysis of student journals, polls, and interviews are presented with a view to capturing and describing how students think and reason with MRS. Data from various assessments such as the FCI and the PEP will be discussed in terms of how conceptual change and MRS work in concert in order to produce epistemological change. However, the quantitative results presented in the next chapter, of the study instruments specified in this proposal, are offered for descriptive purposes only, and are not intended to form the basis for any inference in this qualitative study.

Chapter 4: Data Analysis and Results

Introduction

It is not known how (a) thinking and reasoning with multiple representational systems (MRS) occurs, and (b) how that sort of thinking and reasoning affects epistemological change in terms of mechanisms and processes—whether cognitive, behavioral, or social—in an IP classroom. A qualitative methodology was used in this study in an effort to develop an understanding of the phenomena from the viewpoint of the participants (Merriam, 2009, 2010). Moreover, given the manner in which meaning is constructed in social settings (Yin, 2011) where the researcher is the primary data collection *instrument* responsible for producing a richly descriptive account of the outcomes (Merriam, 2009, 2010), a qualitative methodology was required. Grounded theory design was used as a means for developing a substantive theory capable of describing the complex interactions that comprise the phenomena of thinking and reasoning with MRS, and its influence on epistemological change within the context of a community college IP classroom.

The goal of this qualitative grounded theory study is to determine the influence that multiple MRS have on IP students with respect to their conceptual frameworks and personal epistemology.

R_1: How do IP students use representational systems in their thinking and reasoning?

R_2: How does the use of MRS in the thinking and reasoning of IP students promote personal epistemological change?

This chapter describes in detail the qualitative results of the study by cataloging the various outcomes of study instruments, interviews, and documentation produced by students in an IP course. A detailed thematic analysis of student documents and discussions/interviews are constantly compared and contrasted with one another and the PEP survey data. Descriptive measures from conceptual inventories normally deployed in an IP classroom setting are also discussed in contrast with the qualitative results described herein. Qualitative results are also described quantitatively in an effort to interpret not only the scope of those findings (Chi, 1997), but also to contrast with individual and group collaborative outcomes (Clarà & Mauri, 2010) that involve multiple phases and dimensions of content analysis that are not easily isolated within one methodological approach (Häkkinen, 2013). Quantitative descriptions of these qualitative data are intended for comparison and contrast purposes only.

Descriptive Data

The sample population for this study consists of 34 IP students with ages ranging from 17 to 42 years of age, purposively drawn from two IP courses at Central Arizona College, located in Coolidge Arizona. Twenty-nine students were selected from the sample population in order to form the study population based on persistence in the course, and adult age status. Four students dropped the course before mid-term, and one student who persisted until the end was under age 18. Thirteen adult students from College Physics (algebra-based) and 16 adult students from University Physics (calculus-based) participated in this study. Table 1, below, describes the distribution of students according to course and gender.

Table 3

Study Population Demographics

		Gender		Total
		F	M	
Course	College Physics	7	6	13
	University Physics	3	13	16
Total		10	19	29

Each course met twice a week for three hours at a time. During week one, the Physics and Reality activity was used to set the stage for scientific discourse by asking questions that require no special knowledge. The primary goal of the activity was to set a collaborative tone for small and large-group settings where consensus and description are required. The Learning the Language activity consisted of several individual activities that attempted to reform the student ideas about arithmetic and representation of number versus quantity—which are essential to the law-making procedures that begin to unfold in the Law of the Circle lab. This lab forms the basis of the next phase where the laws of motion are constructed and analyzed for conceptual content, as well as analytical capacity. Students were then polled about the various versions and interpretations of those versions where an axiom is positioned against a natural language explanation. All of this happened within the first 3-4 weeks of the course. The post-testing and exit interviews occurred during the fifteenth and sixteenth weeks of the course, respectively.

The Physics and Reality, and Math-Science-Physics and Reality classroom events occurred during four separate 3-hour meetings in the first week of classes held on August 18, and August 20, 2014 for both IP groups, and consisted of 17 different observations during that time interval. A total of 99 pages of small and large group interview/discussion transcripts were collected for this event, consisting of 4 hours and

51 minutes of audio recordings spanning 39,667 words comprising 39% of the overall transcript data. Twenty-nine students submitted a total of 56 journal documents associated with the interview/discussion activities occurring on the two days of this event.

The Learning the Language classroom events occurred during four separate 3-hour meetings held on August 25, and August 27, 2014 for both IP groups, and consisted of 19 different observations during that time interval. A total of 102 pages of small and large group interview/discussion transcripts were collected for this event, consisting of 3 hours and 46 minutes of audio recordings spanning 41,660 words comprising 41% of the overall transcript data. Twenty-nine students submitted a total of 56 journal documents associated with the interview/discussion activities occurring on the two days of this event. A follow up activity to the Law of the Circle activity was the creation of the First and Second Zeroth Laws (FZL and SZL)—which utilized the methods developed in the Law of the Circle activity in order to create two conventional equations of motion. No interview data was collected for the FZL and SZL (poll reflections. However, 18 out of the 29 participants submitted journal reflections on the content of the core activity and the follow up poll.

The Exit Interview classroom event occurred during two separate 3-hour meetings held on December 10, 2014 for both IP groups, and consisted of 8 different observations during that time interval. A total of 37 pages of small and large group interview/discussion transcripts were collected for this event, consisting of 2 hours and 11 minutes of audio recordings spanning 19,633 words comprising 19% of the overall transcript data. Twenty-seven students submitted a single journal document answering the interview questions described herein before attending the semi-structured interview.

A total of 238 pages of transcript data were collected during this study covering 44 different classroom observations. Coding for both the interview data and journal data consisted of 2,597 references covering 853 sources as collected and arranged within the NVivo software used for this analysis, as illustrated in Table 4 below. Codes for gender, student, and course are not included in these totals, which strictly represent the a priori theoretical codes and in vivo coding activity.

Table 4

Interview Transcript Data

	Page Count	Word Count	Percentage
Physics and Reality	99	39,667	39.3%
Learning the Language	102	41,660	41.3%
Exit Interview	37	19,633	19.4%
Total	238	100,960	100.0%

Data Analysis Procedures

The first step of data analysis is open coding for the identification of key words, and word groupings in the data (Saldaña, 2013). Step two of data analysis follows with In vivo codes when important words and word groupings warrant their own code label. Groups of related codes form categories that can become theoretically saturated when new data analysis returns the same codes (Birks & Mills, 2011). Constant comparison of current activities to prior activities, researcher memos on the current and prior activities, group interview transcripts, and emergent themes and patterns in all of the artifacts produced by the study population were coded within Nvivo in an effort to reach saturation. NVivo codes can be analyzed for relationships and subsequently displayed in multiple graph formats ranging from bar charts to cluster analysis maps that reveal the relationships that exist between nodes (codes) and/or families of nodes (Bazeley & Jackson, 2013).

Two coding schemes—a priori theoretical and indigenous in vivo—were employed in this study. The theoretical codes flow directly from the research questions, and the definitions for the constructs of thinking and reasoning that the author-researcher has derived from the literature. Per the research questions concerned with the constructs of thinking and reasoning with MRS for epistemological change, at least four basic theoretical codes are warranted: thinking in terms of coordinations and distinctions, reasoning in terms of transformation on thinking, representation, and epistemology in terms of expressed belief. Additionally, the 8 elements of thought by Paul and Elder (2008) were used as a priori theoretical codes.

A total of 16 memos were recorded during the analysis, and illustrate decisions made about in vivo coding, theoretical coding, and theoretical development during the coding process. The theoretical codes of Distinctions, Coordinations, and EoT all contain some number of child code relationships.

The child codes for Distinctions consist of various is and is not types of statements concerning math, science, physics, and reality, and are listed in Table 9 below. In each case for these child nodes, the coding process involved assigning the code to statements that were explicitly in that form, or were deemed to satisfy the code definition. Details on the parent-child code relationships are provided below.

Coding schemes. Coding schemes were constructed on the basis of research questions asking how students think and reason with MRS for the sake of epistemological change. The key terms of thinking and reasoning were coded for by means of a priori theoretical codes, whereas personal epistemology was coded for in vivo as the difference between content of beliefs and the structure and process of belief construction emerged within the data. Two themes emerged that matched the research questions: belief development and claims about Thinking, Reasoning, and Understanding—or TRU Claims.

The parent code Beliefs is an a priori theoretical code addressing the epistemological aim of the research questions, and consists of the in vivo child codes Belief Development, Changed Belief Influence, and Old Beliefs. Beliefs is a container for old beliefs and the factors that influence a change in beliefs. Belief Development refers to statements that indicate a change in, or new way to form beliefs, whereas Changed Belief Influence refers to claims about the cause for a change in particular beliefs. Old Beliefs code for statements that indicate what a belief changed from.

The parent code Coordinations is an a priori theoretical code addressing reasoning and consists of the in vivo child codes Collections, I Believe Because, IF-THEN or Because, and Related Things. Coordinations code for the relationships that students encode for when relating two or more of the distinctions coded for under the parent node called Distinctions, and essentially identifies the ability to categorize. Collections is a code that identifies when students combine multiple concepts in an effort to describe their beliefs or ideas, and essentially represents the ability to classify. The I Believe Because code identifies statement that explicitly state a point of view in those terms or its equivalent. IF-THEN or BECAUSE encodes for statements that employ those very words and/or the same reasoning process. The Related Things code describes lists encoded by students in an effort to express a common relationship among multiple concepts.

The parent code Distinction is an a priori theoretical code designed to capture the conceptual content of thinking in terms of the distinctions that student make—such as the categorical operation of IS and IS NOT in reference to various concepts. In particular, the in vivo child codes associated with Distinctions include Physics IS reality, Physics IS NOT reality, etc. A total of 16 different sub-Distinction codes were created, and are described in detail in Table 9 below.

The Elements of Thought (EoT) parent code is an a priori theoretical code for capturing the EoT as described by Paul and Elder (2008). The child codes of Assumptions, Concepts, Implications, Information, Interpretation, POV, Purpose, and Question are described extensively in the literature review chapter. The POV was expanded in to two child nodes—Individual and Group—in order to account for the two types of activities where students were asked to express individual opinions versus a group consensus. Detailed results of this coding scheme are described in Table 10 below.

The Transformations parent code is an a priori theoretical code attempting to capture the creation of new ideas with a view to how that intersects with the Collections, Distinctions, and Coordinations code sets. The in vivo codes of Thinking Claim, Reasoning Claim, and Understanding Claim were created to code for students explicitly describing how their thinking, reasoning, or understanding has changed when asked those very questions—such as during the exit interview described by Table 2 below. Two additional in vivo codes for Questions and Reactions to Others were created in an effort to catalog the general questions that students raised which were not part of the Question EoT scheme, as well as which decisions were based on interaction with other participant's ideas.

A priori theoretical codes for Thinking and Reasoning were deployed late in the coding process due to an effort to give other a priori codes about those constructs primacy, as well as a general lack of clarity in the data upon which to discern what the models described by students actually were. The subsequent process of attempting to code for these constructs once the data lent itself to the scheme, led to a discovery concerning the conceptual framework that is necessary for thinking that is described in chapter 5 as the Cognitive Modelling Taxonomy for Conceptual Frameworks (CMTCF).

Triangulation of data. The research questions concerning how MRS are used in the thinking and reasoning of IP students for epistemological change were answered by analyzing four sources of data: written journals, small and large group discussions/interviews, polling data, and researcher memos. Moreover, two main coding schemes—a priori theoretical and in vivo—were used during data analysis. Coding patterns were consistent between written and narrative sources regardless of whether or not the event was a group activity or an individual reflection, and are described fully in the results section that follows. Furthermore, the results of quantitative measures such as the PEP showed patterns of change that were consistent with the qualitative findings of this study. Those results are also described fully in the next section. The general validity of this study emerges from the coherence between these sources. External validity is the qualitative equivalent of generalizability, and is contingent on the perception that other researchers have regarding the transferability of findings to other domains. The theory produced by this study has potential import to general, educational, and cognitive psychology, as well as human and machine learning.

According to Yin (2014), rich data, respondent validation, triangulation, quasi-statistics, and comparison are effective strategies for defeating threats to validity in qualitative research. Triangulation was achieved through the comparison of both group and individual sources of qualitative data longitudinally through multiple events until persistent themes were detected. Expert panel review of these findings served to confirm the results as consistent and valid within the data itself, and with respect to the researcher memos. Rich data was obtained in terms of the sheer volume of data—such as 238 pages of transcribed interviews, and 2,597 references coded in 853 sources. Respondent validation in the exit interviews confirmed central features of the research questions in terms of participant experience relative to thinking, reasoning, and understanding. As described in the introduction to this chapter, quantitative descriptions—or quasi-statistics—have been used extensively for the sake of comparison and contrast within and between data sources. Multiple events within the study permitted a constant comparison of study outcomes in different contextual settings with the same set of participants. Together, these practices during the study phase support the general validity of the study outcomes.

The limitations of these findings are restricted to the depth and breadth of the collected qualitative data—which comes in the form of written journals and transcribed interviews—and the coding process itself. Overall coding consisted of 2,597 references in 853 sources. Twenty researcher memos were written during the process of coding analysis, which subsequently led to the creation of a new theory based on the data. A total of 238 pages of small and large group discussion/interview transcripts were also analyzed. Given the size of this data set, and the varied nature of its content, there is no reason to suspect missing data. However, given the large number of theoretical and in vivo codes employed by the study, it is possible that certain coding errors might have occurred in this large data set. The results section shows the consistency between theoretical and in vivo coding outcomes, as well as the extensive reach of all coding schemes, and therefore suggests that there is no viable source of these error types therein. It is possible, however, that certain theoretical codes specified in the Proposal were incorrectly coded for—such as the EoT codes by Paul and Elder (2008) that were used in this study. The likelihood of incorrectly coding is extremely low given (a) the simplicity of the constructs defined by Paul and Elder (2008), as well as (b) the consistent application of those codes in a manner that led to the discovery of conceptual frameworks within the emergent theory proposed herein.

Researcher bias is another possible limitation that has been accounted for through the bracketing of researcher opinions in the form of memos created throughout the coding analysis process. A priori theoretical codes based on literature review, in parallel with researcher-produced in vivo coding schemes, served to balance researcher bias against consensus views within the field of study. As the results herein reveal, researcher bias was minimized well within acceptable constraints. The limitations of incorrect coding and missing data have the potential to reshape the thematic results. However, given the extensive amount of data described herein, it is unlikely that either limitation is relevant given the internal consistency of theoretical and in vivo coding procedures that were employed.

Results

The following sections provide the results of study components described in the Proposal. The primary instrument for measuring epistemological change (the PEP), as well as other miscellaneous assessments (FCI, MBT) are detailed first. It should be noted that these quantitative results are provided strictly for the purpose of providing descriptive data on elements of the Proposal that were material to the overall study goals—but not directly part of the research questions. Two main types of analysis on the qualitative data were performed—cluster analysis and node matrices, as well as constant comparative analysis through memo bracketing. Cluster analysis compares codes or families of codes against one another by calculating a similarity index based on either linear regression or coding set intersections. Node matrices simply cross-tabulate individual node comparisons, and thus provide the user with a sense of how frequently various texts coincide—or share a single code value. These measures are intended for description only, and in no way provide quantitative support to the inferences made herein.

PEP Analysis. All 29 students from the study population took the PEP survey in both pre- and post-test conditions, with results shown below in Table 2. The COMPOSITE score is the mean value of the PEP-dimension—Rational, Empirical, and Metaphorical—scores obtained in either test condition, as shown in Table 3 and Table 4, and per course as shown in Table 5. Results show an overall increase in composite PEP scores, as well as an average increase of approximately 3 points along each dimension of the PEP. Changes in the range and standard deviation for pre-post dimension scores reveal an overall decreased variance in the data simultaneous to an overall increase in each dimension of the PEP instrument. The following quantitative data is given for descriptive purposes only, and to address outcomes specified in the Proposal.

Table 5

PEP Dimension Scores

College Physics	Pre-test *M(SD)*	Post-test *M(SD)*
Rational	111.2(9.6)	114.6(10.3)
Empirical	111.5(11.5)	107.5(11.2)
Metaphorical	104.7(12.8)	100.1(8.9)
University Physics	Pre-test *M(SD)*	Post-test *M(SD)*
Rational	111.4(12.8)	116.2(11.5)
Empirical	102.1(11.10)	111.2(9.5)
Metaphorical	93.6(14.4)	101.8(15.7)
Combined	Pre-test *M(SD)*	Post-test *M(SD)*
Rational	111.3(11.2)	114.7(10.1)
Empirical	106.3(12.3)	109.4(10.6)
Metaphorical	98.6(14.8)	101.0(13.4)

Tables 6 and 7 provide aggregate descriptions of changes in PEP scores with respect to PEP dimension in both pre- and post-test conditions.

Table 6

Basic PEP Composite Descriptive Statistics

	n	*Range*	*M*	*SD*
preCOMPOSITE	29	45.33	105.40	11.39
postCOMPOSITE	29	39.00	108.34	9.37
PEP_Change	29	60.00	2.94	13.18

Table 7

Basic PEP Dimension Descriptive Statistics

PEP Dimension	*n*	*Range*	*M*	*SD*
preRATIONAL	29	44	111.31	11.68
preEMPIRICAL	29	52	106.34	12.47
preMETAPHORICAL	29	65	98.55	15.03
postRATIONAL	29	42	114.66	10.31
postEMPIRICAL	29	44	109.38	10.74
postMETAPHORICAL	29	58	101.00	13.68

Twelve of the 29 students in this study retained their primary PEP dimension (D1) as rational, whereas 5 students switched their primary dimension from empirical to rational. No students changed from the primary dimension of metaphorical to rational. According to Table 5, approximately the same number of students switched D1 from empirical to rational (n = 5) as did those who switched from rational to empirical (n = 4). One student retaind D1 as metaphorical, while 3 students retained D1 as empirical. Overall, 17 percent of the study population shifted their primary PEP dimension to rational, while 41 percent retained the rational dimension for D1. The remainder of changes in D1 are given below in Table 5. The following quantitative data is given for descriptive purposes only, and to address outcomes specified in the proposal.

Table 8

Primary PEP Dimension Changes

preD1	postD1	Matching nodes	
		n	%
R	R	12	41
E	E	3	10
M	M	1	3
R	M	2	7
E	R	5	17
M	R	0	0
R	E	4	14
E	M	1	3
M	E	1	3
	Total	29	100

Six of the 29 students in this study retained their secondary PEP dimension (D2) as empirical, whereas 3 students switched their secondary dimension from rational to empirical, and 3 students swtched from metaphorical to empirical. Another 6 students retained the rational dimesions for D2 between pre- and post-test conditions, whereas only 3 retained the metaphorical dimesion for D2. Overall, 42% of the sample population retained the secondary PEP dimension (D2) between pre- and post-test conditions, with an equal amount retaining the rational dimension as did those who retained the empirical dimension. Ten percent of students in this study retained the metaphorical dimension for D2. The remainder of changes in D2 are given below in Table 9.

Table 9

Secondary PEP Dimension Changes

preD2	postD2	Matching nodes	
		n	%
R	R	6	21
E	E	6	21
M	M	3	10
R	E	3	10
E	M	2	7
M	E	3	10
R	M	1	3
E	R	4	14
M	R	1	3
	Total	29	100

Fourteen of 29 students in the study population retained metaphorical as their last PEP profile dimension (D3), whereas only three students retained the empirical dimension, and no students held the rational dimension between pre- and post-test conditions. An equal number of students (*n* = 5, 17%) switched D3 from empirical to metaphorical, or vice versa. The remainder of changes in D2 are given below in Table 7.

Table 10

Tertiary PEP Dimension Changes

preD3	postD3	Matching nodes	
		N	%
R	R	0	0%
E	E	3	10%
M	M	14	48%
R	M	1	3%
E	R	0	0%
M	R	1	3%
R	E	0	0%
E	M	5	17%
M	E	5	17%
		29	100%

All pre-post scores, and the overall PEP change are normally distributed, as shown by Shapiro-Wilks (SW) normality tests in Table 11—which is given for descriptive purposes only, in accordance with what is generally appropriate for an instrument of this type. Epistemological change of the type measured by the PEP instrument is part of the naturally occurring background of the study environment, rather than a study outcome falling under the lens of qualitative design. The PEP was specified in the Proposal, and the content of the PEP is material to the research questions; therefore, these descriptive statistics are offered for description only, rather than for inference of any sort.

Table 11

PEP Score Distributions Normality Tests

	Kolmogorov-Smirnova			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
preRATIONAL	.166	29	.040	.937	29	.083
preEMPIRICAL	.114	29	.200*	.972	29	.619
preMETAPHORICAL	.106	29	.200*	.970	29	.549
postRATIONAL	.095	29	.200*	.951	29	.189
postEMPIRICAL	.104	29	.200*	.969	29	.530
postMETAPHORICAL	.137	29	.172	.941	29	.107
preCOMPOSITE	.122	29	.200*	.946	29	.146
postCOMPOSITE	.100	29	.200*	.973	29	.650
PEP_Change	.143	29	.132	.969	29	.525

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Qualitative analysis.

Overall math science physics and reality sequence. Combined coding of the Physics and Reality, and the Math-Science-Physics-Reality journals, and small/large group discussions/interviews is shown in Table 12 below, according to the codes, and the number of sources and references coded. The first two memos created while coding this source data detected a pattern of distinction making concerning the connection between physics and reality—which led to the 8 distinctions listed below. The Collections, Coordinations, and Transformation codes were created based on a memo entry that noted how students were collecting concepts and distinctions in an effort to create new ideas. The fourth memo entry noted a pattern of question-asking in the source data that was in some way connected to both the thinking and reasoning of students in the sample population, as well as revealing the epistemic stance and/or doubt therein.

Table 12

Overall Coding Results

Select codes and *sub-codes*	Sources		References	
Beliefs	49		104	
Belief Development		*22*		*35*
Changed Belief Influence		*27*		*35*
Old Belief		*18*		*20*
Coordination's	115		338	
Collections		*43*		*75*
I Believe Because		*62*		*96*
IF-THEN or BECAUSE		*34*		*57*
Related Things		*60*		*109*
Distinctions	92		688	
Math DOES		*32*		*67*
Math IS		*28*		*62*
Math IS NOT Reality		*9*		*10*
Physics DOES		*49*		*100*
Physics IS		*70*		*128*
Physics IS NOT or DOES NOT		*3*		*3*
Physics IS NOT Reality		*51*		*74*
Physics IS Reality		*12*		*14*
Physics is Reality MAYBE		*4*		*4*
Reality is		*50*		*81*
Reality IS NOT		*3*		*3*
Science DOES		*26*		*48*
Science IS		*35*		*78*
Science IS NOT Reality		*8*		*8*
Science IS Reality		*4*		*4*
Transformations	30		43	
	286		1173	

Table 13 below provides data on the coding for journal submissions and small/large group discussions/interview results in terms of the Elements of Thought as described by Paul and Elder (2008), as they pertain to both the Physics and Reality and the Math-Science-Physics-Reality activities. Given the collaborative nature of the activities, it was necessary to code Point-of-View (POV) as either individual or group—depending on the specific journal question and/or group activity. Transcripts of group discussions/interviews, as well as individual journal assignments made explicit reference to the type of POV that was being expressed, and thus led to coding POV as either Group or Individual.

Table 13

Coding Results for the Elements of Thought (EoT)

Codes and *sub-codes*	Sources	References
Elements of Thought	109	571
Assumptions	*16*	*21*
Concepts	*69*	*194*
Implications	*40*	*67*
Information	*9*	*10*
Interpretation	*55*	*88*
POV	*23*	*73*
Purpose	*9*	*12*
Question	*43*	*106*

Demographics codes for Course, Gender, and Student have been omitted and listed in Table 1.

Figure 4 below is a circle graph illustration of the connection between statements made by students indicating that science is what math is or does, math is what science is or does, as well as the strong connection between the beliefs that science and math are not equivalent to reality, but merely ways to describe it.

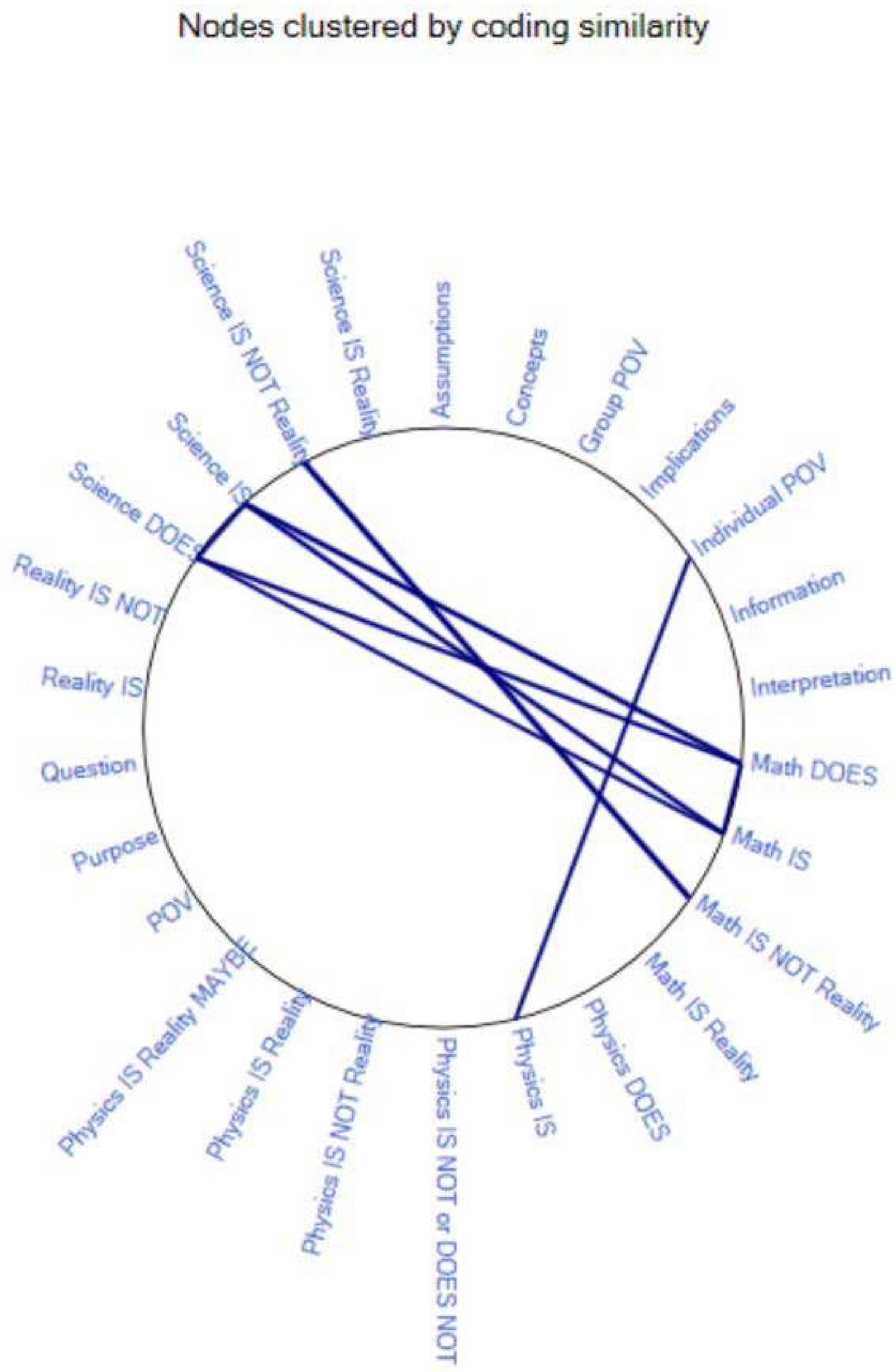

Figure 4. Cluster analysis circle graph for EoT and distinctions.

The associative strength between codes related to student opinions illustrated in Figure 4 were measured using the Jaccard Index for similarity—which is based on a part-whole relationship between the number of common code references (intersection of sets) relative to the total number of codes entered in the union of sets (Levandowsky & Winter, 1971). Table 14 below lists the relevant Jaccard Indices for Figure 4.

Table 14

Jaccard Indices for Distinction and EoT Code Comparison

Node A	Node B	Jaccard Index
Science IS NOT Reality	Math IS NOT Reality	1.00
Science IS	Math DOES	0.91
Science IS	Math IS	0.81
Math IS	Math DOES	0.78
Science IS	Science DOES	0.78
Science DOES	Math DOES	0.75
Physics IS	Individual POV	0.71
Science DOES	Math IS	0.71

Cluster analysis on the codes: Distinction and Elements of Thought (EoT). Indices less than 0.70 are not graphed in Figure 4, and therefore do not appear in this table.

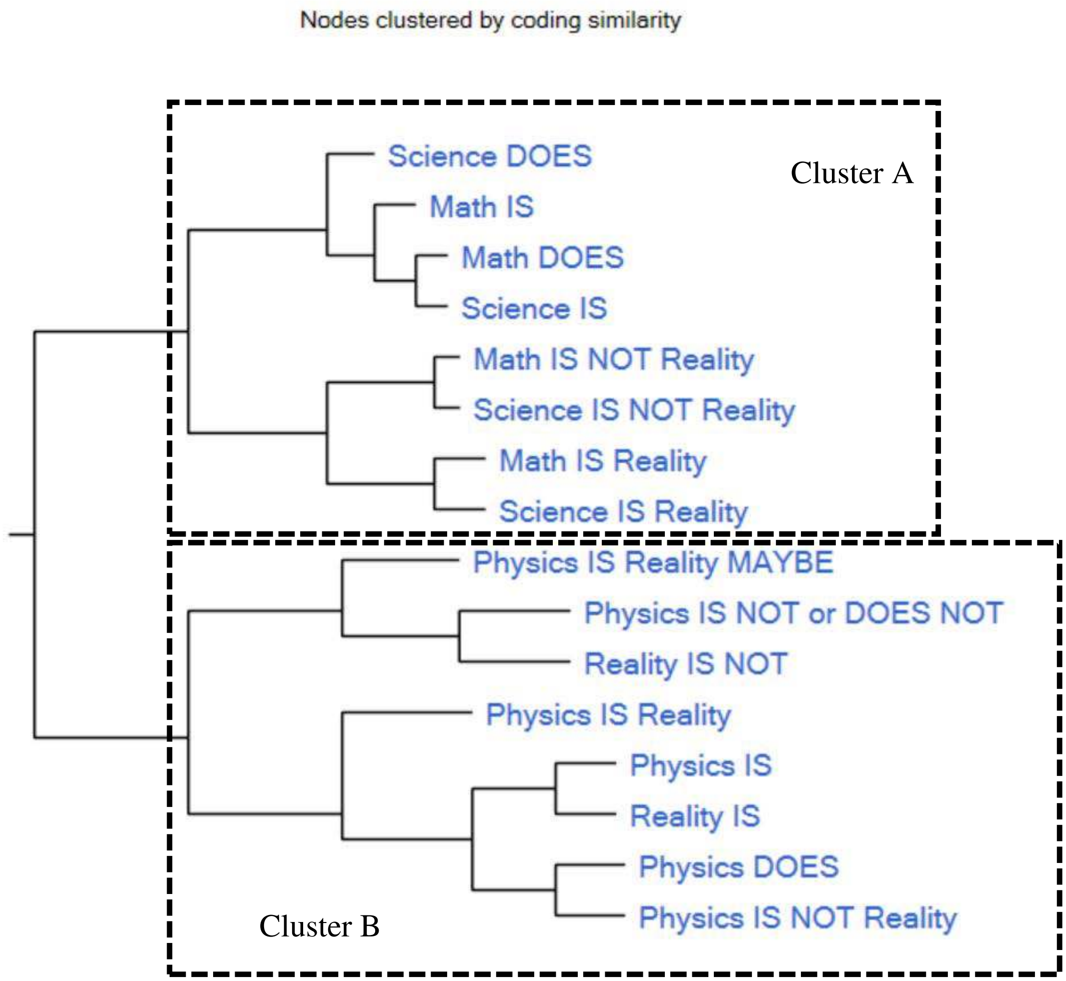

Figure 5. Cluster analysis dendrogram.
A dendrogram is a hierarchical *tree* structure with branches, sub-branches, and leaves. The right-most leaves are the most similar. Leaves on a branch have a strong relationship in terms of co-occurrence within source material.

Cluster B consists exclusively of code pairings involving a point of view relating physics and reality. Student opinions illustrated by this cluster indicate concepts of what physics does is strongly related to the point of view that physics is not reality because it is about reality. The connection between opinions about what physics is, and what reality is, are disjoint from the decision about the nature of physics as either reality or not reality. The distinctions of IS and DOES describe statements that define the object of each code in terms that are either process/product oriented (DOES), or more abstract in terms of what the term is like or about (IS). Moreover, the decision that physics is reality is quite distant from the pairing of the aforementioned sub-clusters. The point of view that physics might be reality (MAYBE code) is contingent on what physics is not, or does not do, in parallel with what reality is not. Each of these distinctions involve a negative conclusion that grounds the uncertainty concerning physics and reality.

During the coding process, the in vivo Collections code was brought into a child relationship with the Coordinations code—which also includes IF-THEN or BECAUSE, Related Things, and I Believe Because child codes—because it matched that a priori theoretical construct partially representative of reasoning. The Coordinations parent code is a container for relationships within or between the collections of Distinctions, whereas the parent node EoT is an a priori theoretical code consisting of 9 child nodes as listed in Figure 6 below. Group POV and Individual POV are child nodes of the EoT POV, and thus expand the original listing of the 8 EoT by Paul and Elder (2008) by one.

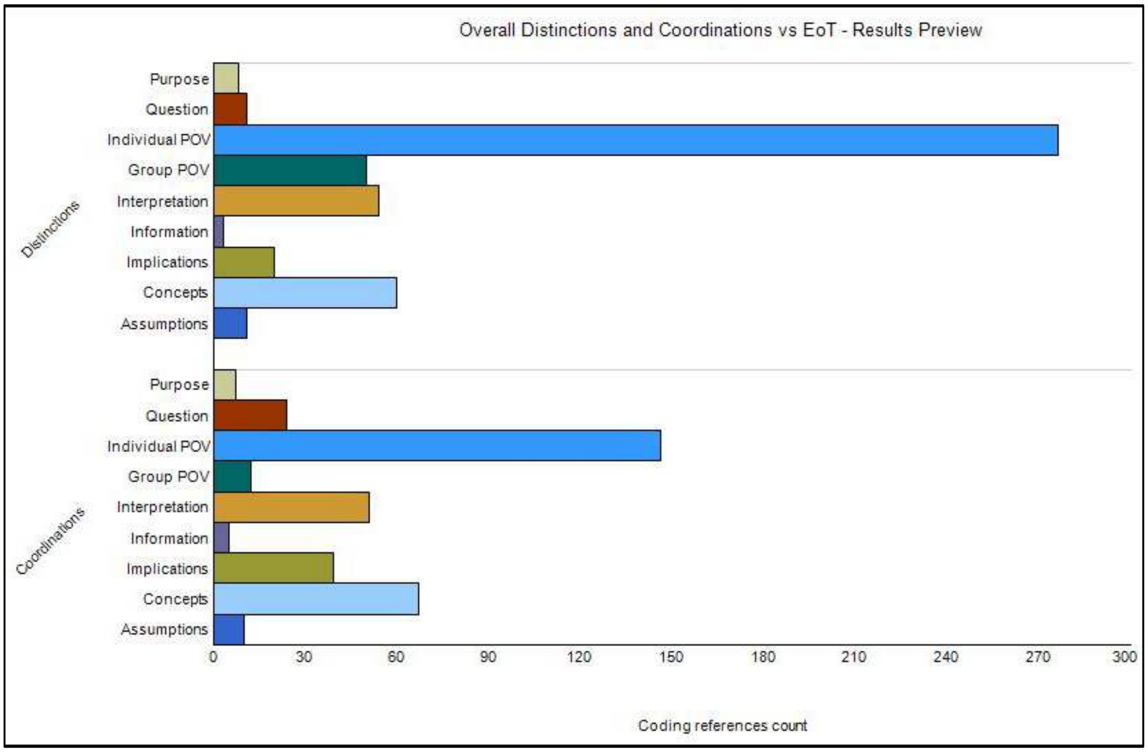

Figure 6. Distinctions and coordinations vs. EoT node matrix.

Individual POV was the largest contributor to how students organized their thoughts as captured by the Coordinations and Distinctions codes. Approximately 56% of the distinction making was in the form of and Individual point-of-view (POV), whereas roughly 40% of Coordinations were in this form. Group POV comprised 10% and 3% respectively to the Distinctions and Coordinations code structure. Conceptual content increased from roughly 12% in Distinctions to 19% in Coordinations. The Distinctions code is an a priori theoretical code representing the construct of thinking in terms of the portion of model construction that requires descriptive metrics (distinctions), whereas Coordinations attempts to provide a container for elements of reasoning. Figure 7 below illustrates the relative percentages from Figure 6. The major shifts illustrated therein include less POV in the transition from Distinctions to Coordinations, as well as an increased usage of Concepts, Interpretation, and the consideration of Implications.

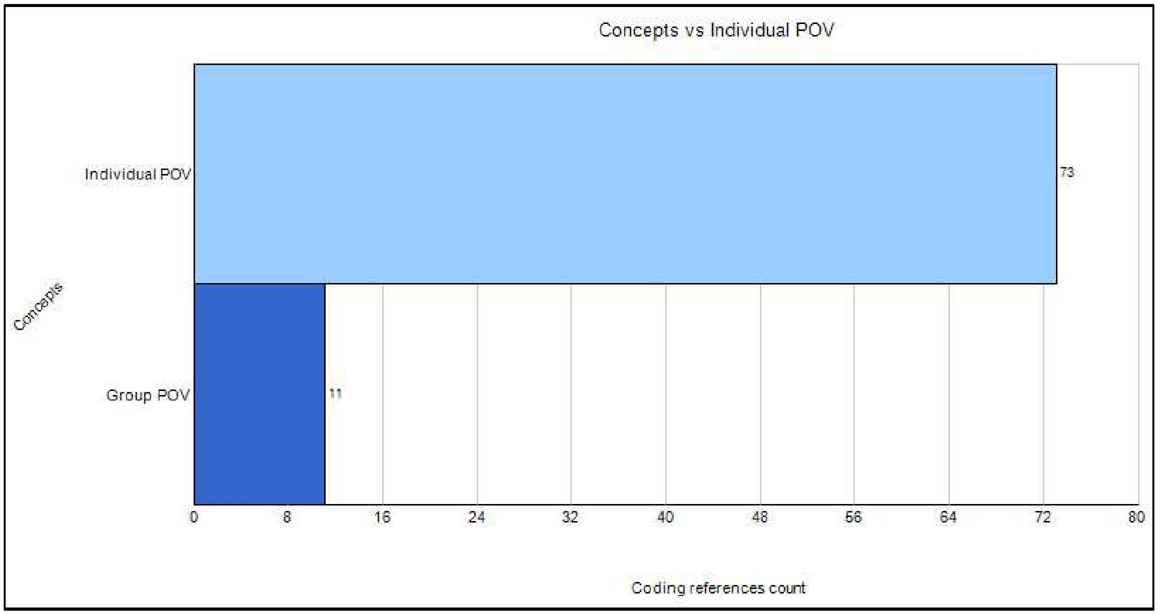

Figure 7. Concepts and individual POV node matrix.

The majority of Concept codes that also coded as POV came in the form of Individual POV across all sources. A total of 71 out of 362 Coordination codes across all sources were Concepts, where as a total of 61 out of 487 Distinctions codes were Concepts. Figure 7 above illustrates the coincidence of Concept and Individual POV codes, whereas Figure 6 above details the occurrence of EoT relative to Distinctions and Coordinations. A total of 148 out of 362 Coordination codes across all sources were Individual POV, where as a total of 277 out of 487 Distinctions codes were Individual POV. The following quotes provide example of the coincidence of Concepts with Individual POV.

Table 15

Examples of Concept Coordination

Student, Source, Date	Quotation
MSUP6, Physics and Reality Journal 1, August 24, 2014	“physics is to reality what a map is to the real world”
FSCP8, Physics and Reality Journal 1, August 24, 2014	“physics is one of the scientific parts of reality
MSCP4, Physics and Reality Journal 1, August 27, 2014	“reality is closely correlated to that of Physics and is indeed a subset of reality”
FSCP2, Math-Science-Physics-Reality Journal 2, August 24, 2014	“Physics is a subcategory of science that involves things that are perceived, such as time, motion, energy"
MSCP4, Math-Science-Physics-Reality Journal 2, August 27, 2014	“mathematics, science, and physics are tools that support and explain concepts of reality"

Figure 8 below illustrates the relative percentages for each of the EoT coincident with either Distinctions or Coordinations. Approximately 20% of the EoT codes that were coincident with Coordinations were Concepts, whereas 12.5% of the Distinction codes coincident with EoT were Concepts. Individual POV comprised 41% of the coincident codes, and 57% of the Distinctions codes were also Individual POV.

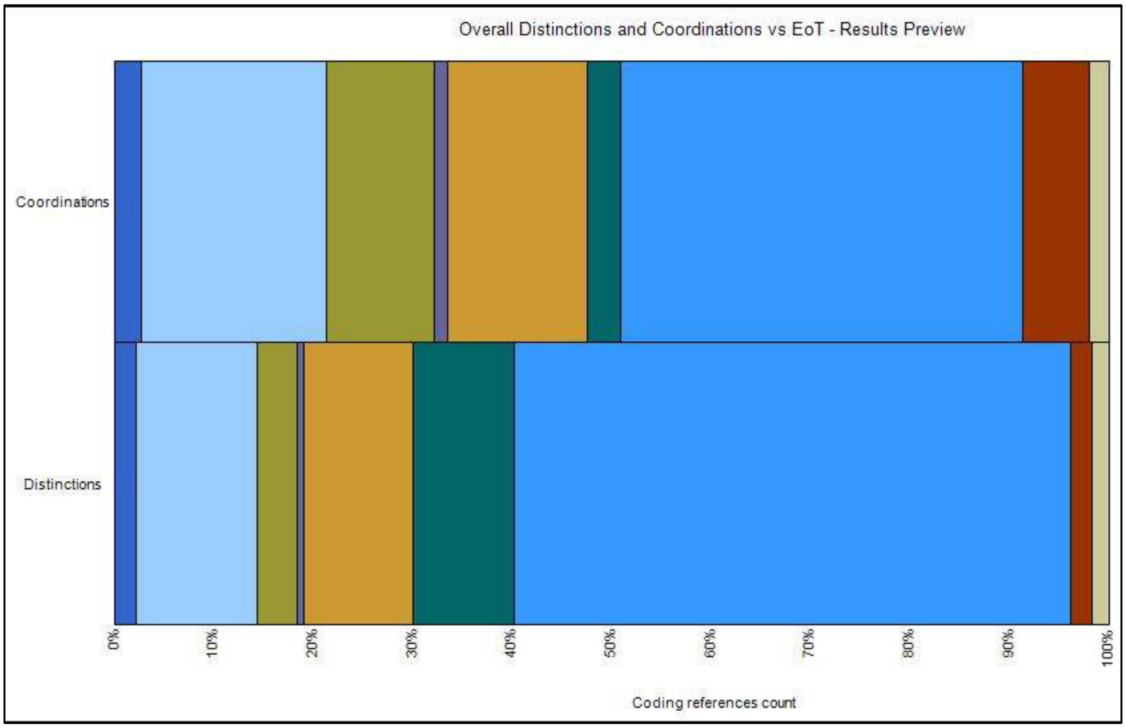

Figure 8. Distinctions and coordinations vs. EoT node matrix.

Figures 9 and 10 below illustrate the pattern of EoT use by students when considering the Math Science Physics and Reality (MSPR) questions in a group setting versus an individual reflection opportunity. In both cases, the usage of EoT is reduced by at least one half when shifting from Distinctions to Coordinations.

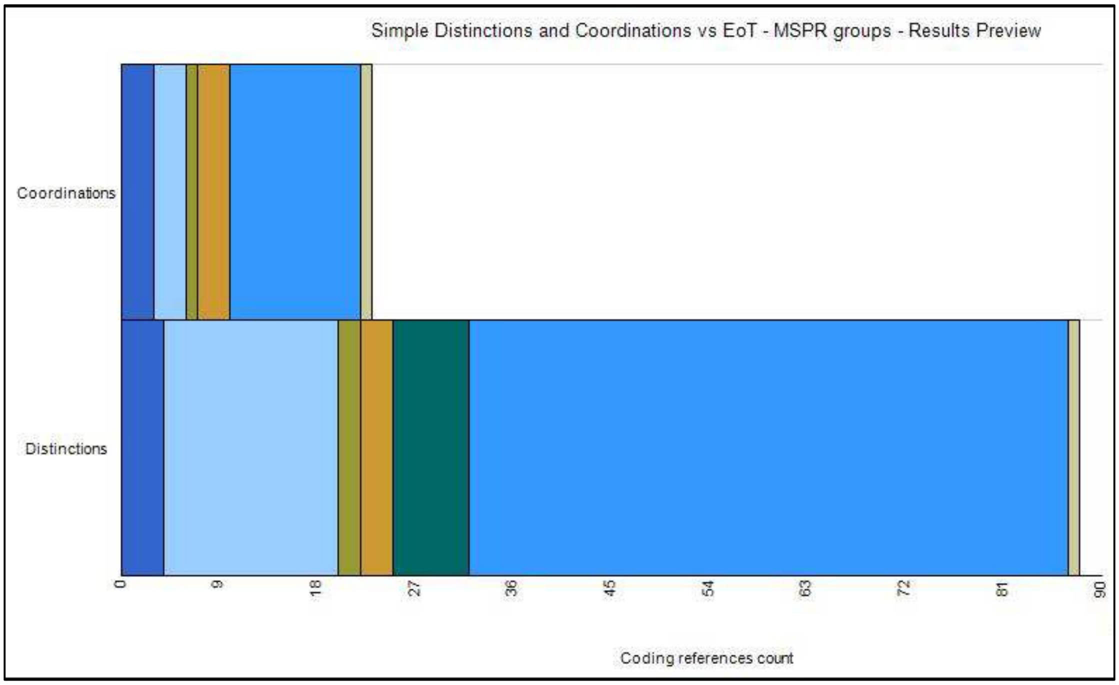

Figure 9. MSPR group discussions distinctions-coordinations EoT node matrix.

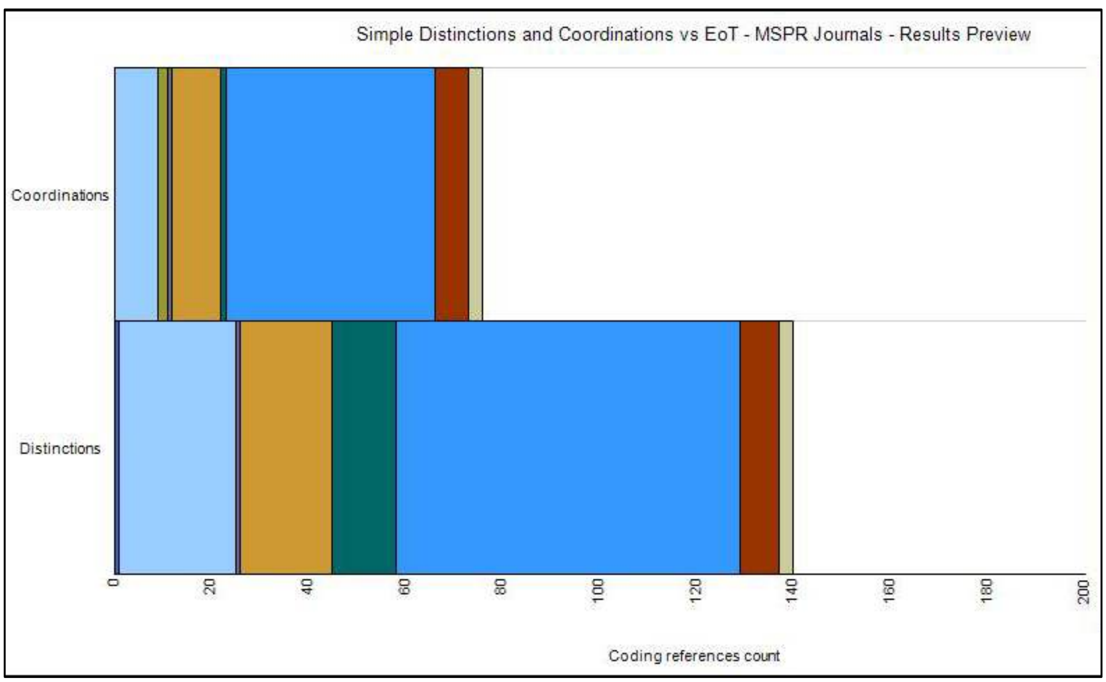

Figure 10. MSPR journals distinctions-coordinations EoT node matrix.

The Distinctions child codes can be grouped into four different collections as illustrated in Figures 11 – 15 below. The Distinction concerning math and reality indicate a dominant disposition to answer the question of whether or not math is reality in terms of what Math IS (*n* = 75) is and/or what Math DOES (*n* = 72). One of the three coding references for Math IS Reality was rooted in EoT Assumptions, whereas the remaining two were expressed as Individual POV. A total of 10 EoT codes comprise the Math IS NOT Reality Distinction—with 1 coded as a Concepts, 2 Interpretation codes, 1 Group POV, and 5 Individual POV codes.

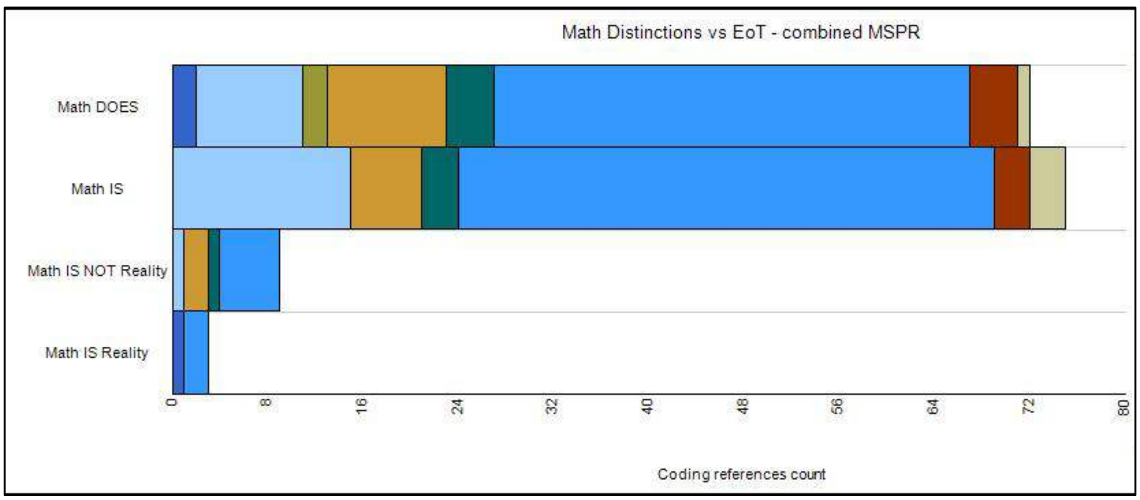

Figure 11. MSPR math EoT node matrix.

Similar results were found for the Science and Reality question in terms of the number of codes generated for the decision to accept or not accept science as reality. One of the five coding references for Science IS Reality was rooted in EoT Assumptions, whereas the remaining four were expressed as Individual POV (*N* = 3), and Implications (*N* = 1). A total of 8 EoT codes comprise the Science IS NOT Reality Distinction—with 1 coded as a Concepts, 2 Interpretation codes, 1 Group POV, and 4 Individual POV codes. However, the relationship between what Science IS and what Science DOES was not as closely matched to the same distinctions relative to math—with a near 2-to-1 ratio between what Science IS (*N* = 93), and what Science DOES (*N* = 53).

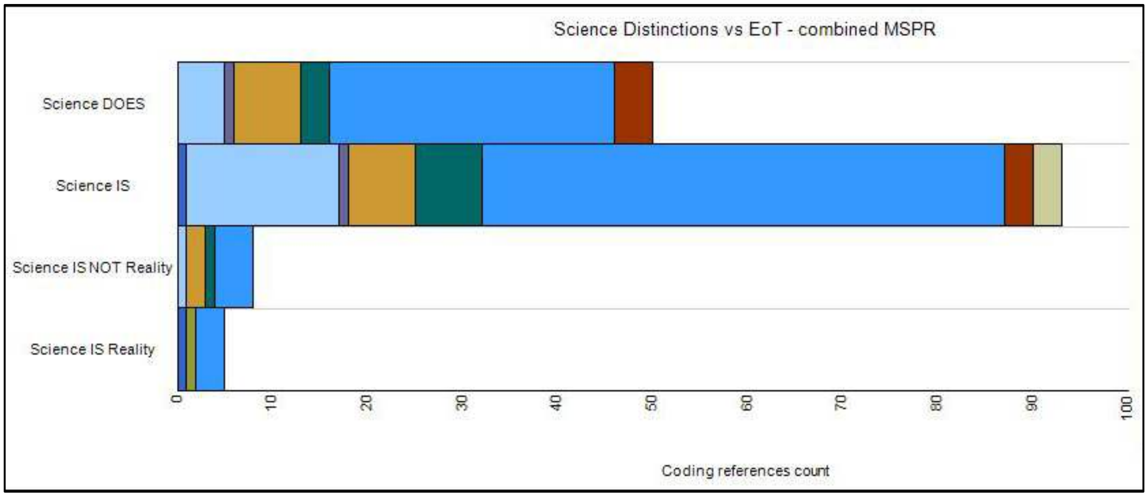

Figure 12. MSPR science EoT node matrix.

The vast majority of Distinctions made about the nature of Physics and Reality came in the form of Physics DOES (*N* = 103), Physics IS (*N* = 146), and Physics IS NOT REALITY (*N* = 81). Fifteen references coded as Physics IS Reality, whereas only 7 coded for Physics IS Reality MAYBE.

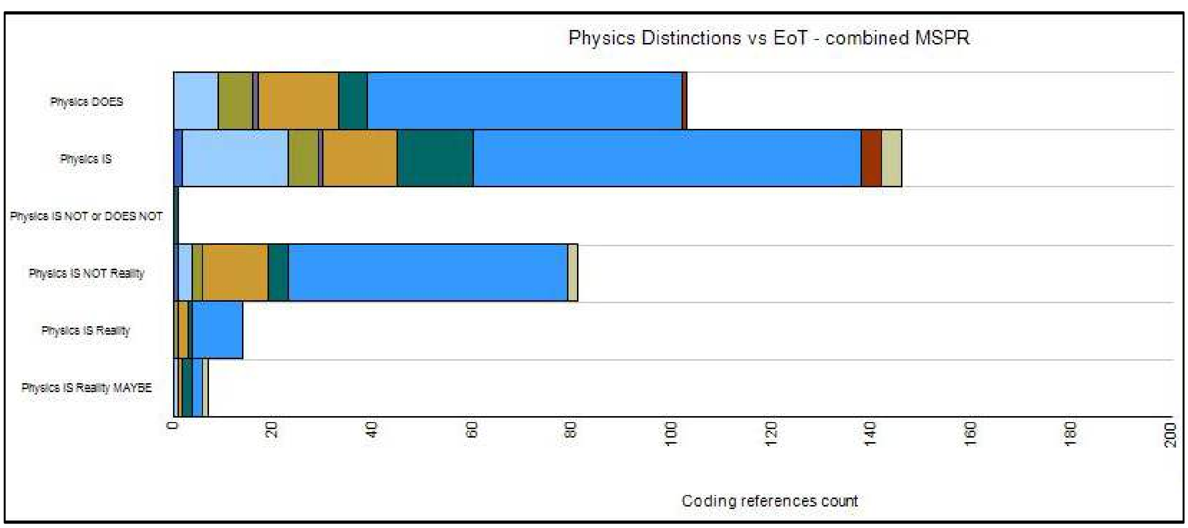

Figure 13. MSPR physics EoT node matrix.

Analysis of the physics and reality activity journals. A closer look at the particular distinctions that students made in the Physics and Reality activity reveals the dominance of individual POV in the reflections offered by students submitting the follow-up journal. Figure 10 below illustrates the relative frequency of relevant Distinctions and their correspondence to the EoT. Assumptions, Information, and Questions were the least used codes, whereas Concepts, Implications, and Interpretation comprised most of the remaining code content in this activity.

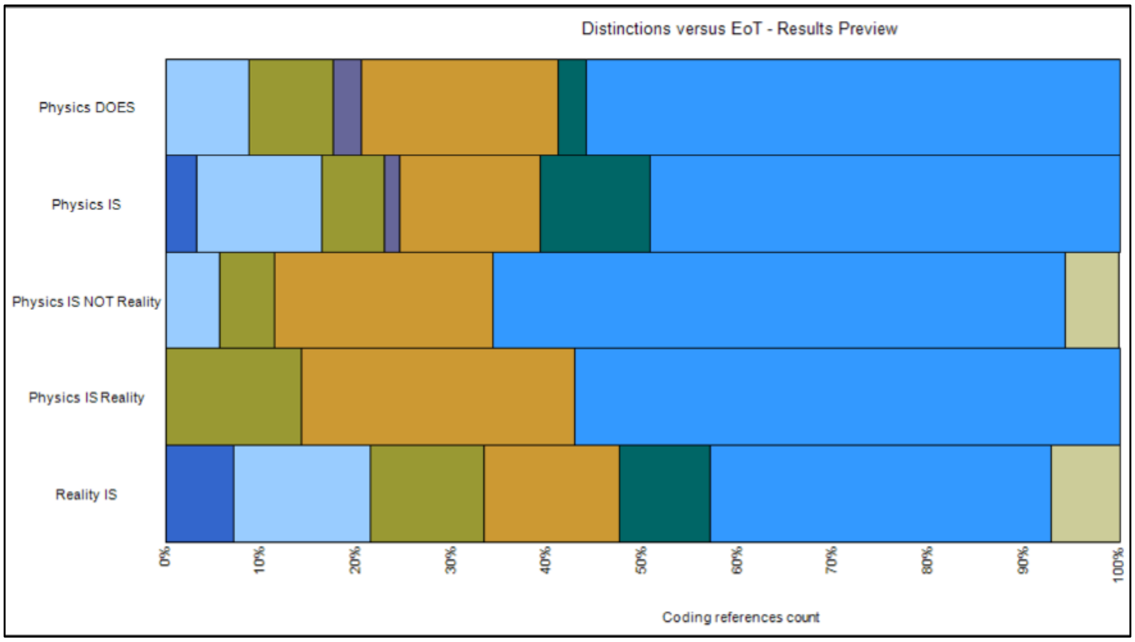

Figure 14. Distinctions vs. EoT node matrix.

A comparison of the Coordinations with EoT reveals a shift in the dominance that POV had over Distinctions—to Interpretation and Implications. The use of Assumptions and Questions also increased when compared to Distinctions—as illustrated in Figure 11 below. The largest shift occurred for IF-THEN reasoning in terms of the Implications that students perceived in their reflections about physics and reality. Statements coded as I

Believe Because, and Related Things, employed all of the EoT, whereas Collections and IF-THEN statements coded for all of the EoT except Information. Assumptions and Questions increased in all four categories of Coordinations.

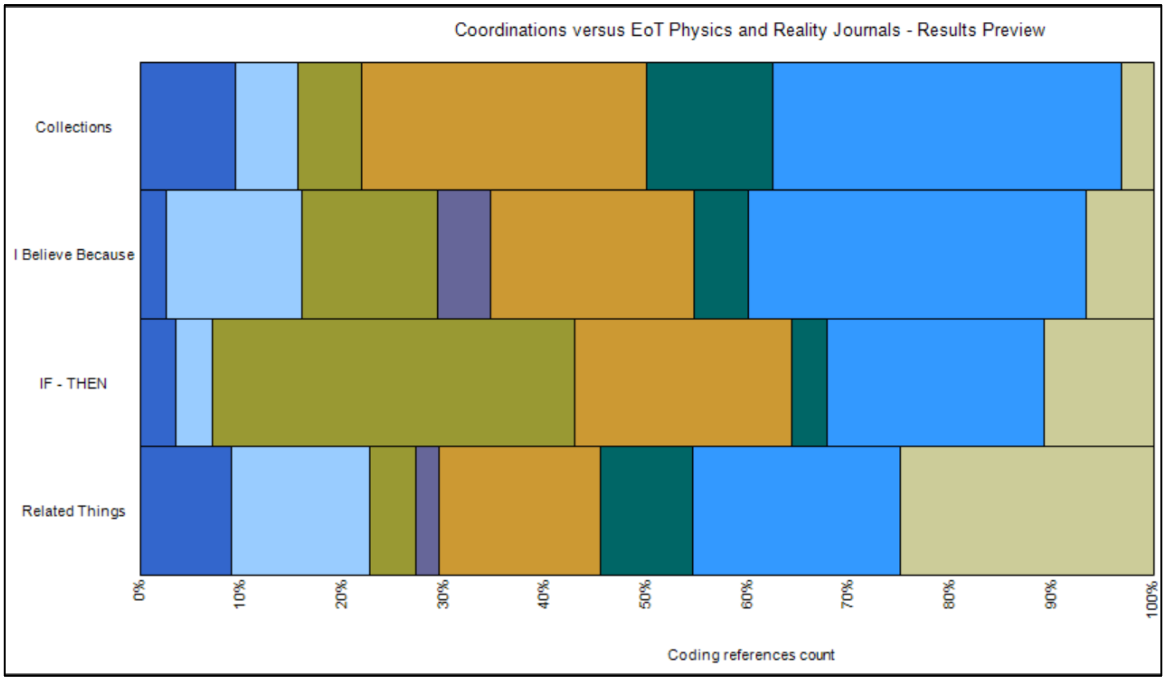

Figure 15. Coordinations vs. EoT node matrix.

Consideration of research questions with current results. The two research questions are (1) How do IP students use representational systems in their thinking and reasoning, and (2) How does the use of MRS in the thinking and reasoning of IP students promote personal epistemological change? Given that the Physics and Reality activity is entirely narrative or written, natural language in those two forms comprise the entire scope of representational systems employed by students thus far. Figures 6, 7, and 8 illustrate how students are using the written natural language representational system, which has been influenced by both small and large-group narratives. Initial results indicate that distinction-making (Distinctions code) employs a different distribution of the EoT than does the synthesis of those distinctions (Coordinations code). In other words, thinking and reasoning within the EoT are potentially distinguishable, as opposed to reasoning being simply another form of thought as suggested by Paul and Elder (2008). These shifts in thinking and reasoning associated with belief formation and change were situated within the collaborative and individual reflections of the participants in the Physics and Reality activity.

The aggregate PEP results (Table 3) indicating large-scale variations (*SD* = 13.18) in epistemology, with small changes in composite personal epistemology (*M* = 2.97). Eleven of the 29 respondents retained their pre-test PEP profile in the post-test condition, 14 experienced a singular shift between 2 of the 3 PEP profile dimension, and the remaining 4 obtained a complete change in PEP dimension profile in the post-test condition. Nine students changed their primary PEP dimension. The degree to which the Physics and Reality activity contributed to these changes in PEP dimension are unknown at this time due to the close proximity of the activity to the pre-test condition.

Combined analysis of the remaining study activities. As a follow up to the MSPR activities, students entered a phase of the curriculum designed to develop mathematical modelling skills need for modelling Physics in the Learning the Language activity (see Appendix E and F). The skills developed in that activity were subsequently used to build conventional laws of motion, and those activities factored into the analysis of polling results concerning the First Zeroth Law (FZL) and the Second Zeroth Law (SZL) created by the students in order to describe motion—such as the basic equations for speed and acceleration (see Appendix G). This is the foundation of the entire course, and subsequent curriculum in support of the course learning outcomes relied heavily on this process throughout the remainder of the semester leading up to the end of term where the exit interviews occurred. Each of these activities posed the same set of questions to students concerning their POV on whether or not they had experiences any changes in their thinking, reasoning, or understanding. Figure 12 below illustrates coding from the activities comparing claims about thinking (T), reasoning (R), and understanding (U)—or what was coded herein as TRU Claims.

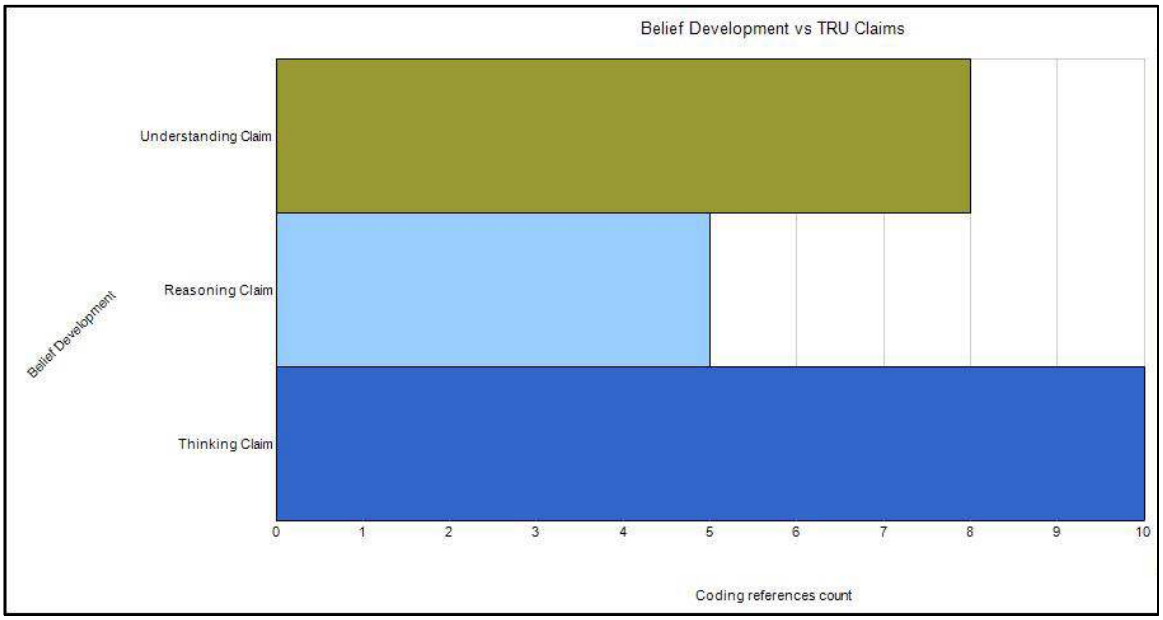

Figure 16. Belief development with TRU claims node matrix.

A total of 54 references to Belief Development were coded in 31 sources, whereas 381 TRU Claims were made in 219 duplicated sources throughout the study data—Thinking Claims sources (N = 71), Reasoning Claim sources (N = 61), and Understanding Claim sources (N = 87). Figure 12 above, shows the intersection of those codes with Thinking Claims (N = 10), Reasoning Claims (N = 5), and Understanding Claims (N = 8). Figure 13 below, illustrates the connection between Belief Development and EoT. The following direct quotes provide a sampling of the coincidence of TRU Claims and Belief Development in terms of Thinking Claims.

Table 16

Examples of Belief Development Claims About Thinking

Student, Source, Date	Quotation
FSCP3, Physics-Reality WRAPUP Journal, September 8, 2014	"I have learned many new avenues of belief development, like compilation of thoughts and ideas, deductive reasoning, and conclusive resolution... PHYSICS!"
FSUP1, Physics-Reality WRAPUP Journal, September 12, 2014	"My thinking did change a lot about these questions and I concluded that there are many answers not one solid answer since everyone will have their own meaning about reality and if physics is reality because all of our thoughts are very different."
FSUP1, Physics-Reality WRAPUP Journal, September 12, 2014	"I have always been a very close minded person when it comes to believing others and their ideas, so no my way of believing did not change, but my way of thinking has."
MSCP5, Physics-Reality WRAPUP Journal, August 30, 2014	"I believe that my thinking has changed a lot after these activities … I believe that I am starting to think outside of the box.
MSUP15, Physics-Reality WRAPUP Journal, September 10, 2014	"Some of the things that have been changed are my thinking, reasoning, understanding, and the way I come to believe."

The following direct quotes provide a sampling of the coincidence of TRU Claims and Belief Development in terms of both Reasoning and Understanding Claims.

Table 17

Examples of EoT Belief Development

Student, Source, Date	Quotation
MSCP4, Physics-Reality WRAPUP Journal, September 9, 2014	"And I came to believe that my previous reasoning didn't allow for the opinions that I didn't quite understand the true meanings of the terms."
MSCP6, Physics-Reality WRAPUP Journal, September 7, 2014	"How I have come to believe has slightly changed as my understanding and reasoning changed."
MSUP15, Physics-Reality WRAPUP Journal, September 10, 2014	"Some of the things that have been changed are my thinking, reasoning, understanding, and the way I come to believe."

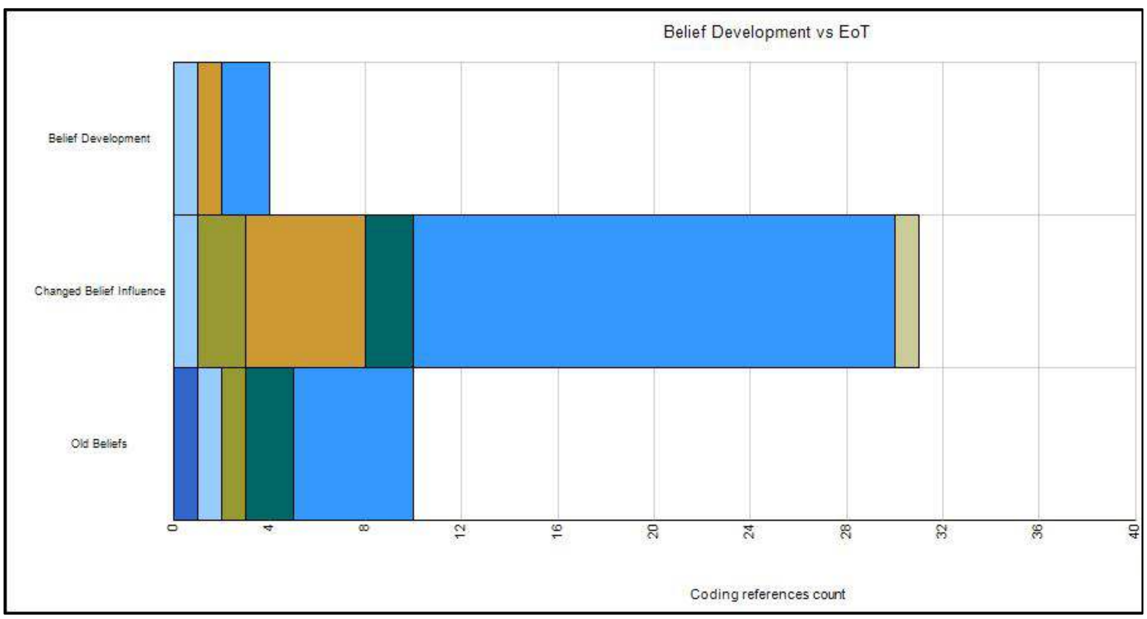

Figure 17. Node matrix comparing beliefs with EoT.

Change Belief Influence (a code tracking a new belief with its cause) was the largest coincidence (*N* = 31) within the family of codes comprising the Beliefs node, which includes Belief Development (*N* = 4). Only 10 Old Belief codes coincide with EOT from the 20 references within 18 sources that originally coded for Old Beliefs. The

Belief Development code specifies a student's perception that the way that they have come to believe in things has changed in some way. Most students did not feel as though they changed the way that they come to believe, but many students did experience a change in beliefs concerning math, science, physics and reality, as indicated herein. Figure 18 below illustrates the connection between TRU Claims and EoT. The following direct quotes provide a sampling of the coincidence of EoT and Belief Development in terms of the child codes Individual POV and Changed Belief Influence.

Table 18

Examples of Belief Development

Student, Source, Date	Quotation
FSCP6, Physics & Reality Journals, August 26, 2014	"I do think physics is reality because it is used in everyday life!"
MSCP4, Physics & Reality Journals, August 27, 2014	"I am now of the opinion that Physics as is all the disciplines of science are merely tools to get to reality."
MSUP11, Physics & Reality Journals, August 27, 2014	"Physics represents Reality...that's as good as it gets."
FSUP2, Physics & Reality Journals, August 27, 2014	"When all that is thought about it would be hard to say physics is reality because there is no particular definition and one definition of reality cannot be isolated to fit the question. If the definition of reality could be distorted to where it only meant what is physically real the yes, physics would be reality, but taking in part of the definition is not possible … physics is not reality."
PHY121 Small group 10 member, Math-Science-Physics-Reality Narratives talk 2, August 20, 2014	"My reality changed a little bit-- my personal thing, I was thinking about it. This is just kind of what I wrote down. I wrote down, Reality is the actual occurrence of things the way they really are. People do not experience different realities, per se, just different parts of the same reality or even seeing the same reality from a different perspective."
FSCP8, Physics-Reality WRAPUP Journal, September 10, 2014	"Now, after the two Journal assignments and the discussions in class, I lean towards 'Physics represents Reality'.

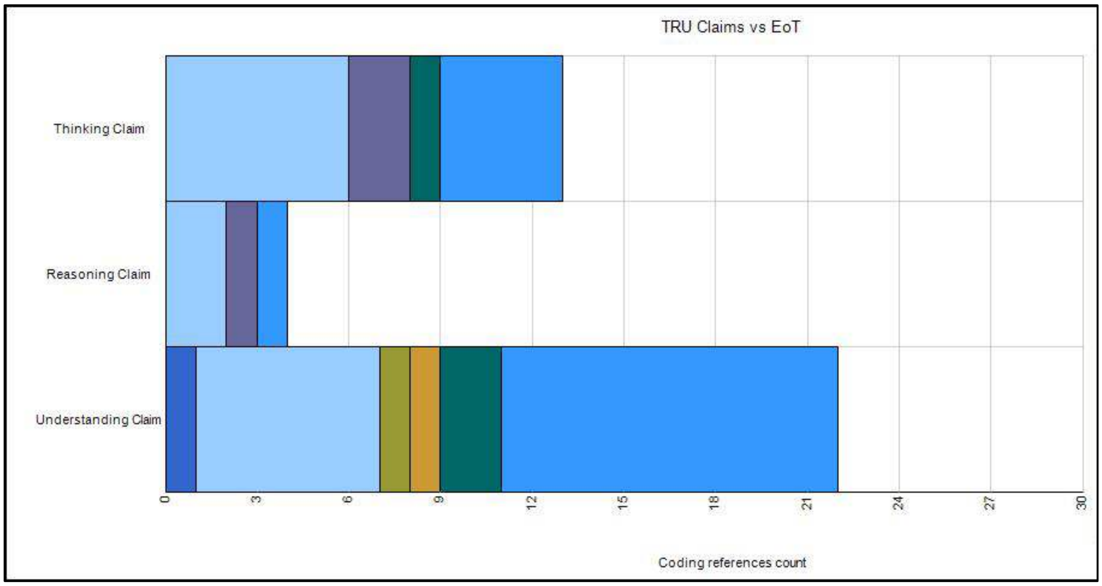

Figure 18. Node matrix comparing true claims with EoT.

Individual POV is the largest component of Thinking Claims (*N* = 13) and Understanding Claims (*N* = 22), while comprising a small portion of Reasoning Claims (*N* = 1). The conceptual content of both Thinking (*N* = 6) and Understanding (*N* = 7) Claims was roughly triple the conceptual content of Reasoning Claims (*N* = 2). Belief Development and Changed Belief Influence coded together 4 times, as demonstrated in the direct quotes from sources given below.

Table 19

Examples of Belief Development

Student, Source, Date	Quotation
FSUP1, Physics and Reality Wrap Up Journal, September 12, 2014	"My thinking did change a lot about these questions and I concluded that there are many answers not one solid answer since everyone will have their own meaning about reality and if physics is reality because all of our thoughts are very different. My thinking I believe also expanded more into other thoughts. I never sat in my room and thought about these questions, ever. So it made my thoughts expand in a different way than they usually do"
MSCP4, Physics and Reality Wrap Up Journal, September 9, 2014	"And I came to believe that my previous reasoning didn't allow for the opinions that I didn't quite understand the true meanings of the terms"
PHY111 Small Group 4, Learning the Language Narratives, September 28, 2014	"I think I learned that it changed my view on how people understand. So two people with different bodies of knowledge can end up at the same conclusion about something, and how different ideas can represent the same concept"
MSCP5, FZL SZL Poll Reflections, September 24, 2014	"I have just been in a groove for so long and thinking they were the same thing that it took me a second to recognize the terms are describing different forms of motion"

Other assessments. The FCI and the MBT were not part of the study in terms of research questions; however, they were part of the standard set of assessments associated with the courses. Twenty-two of the 29 study participants completed both the pre- and post-test FCI with results shown in Table 19. Twenty of the 29 study participants were present to take the MBT with results shown in Table 20. According to Hake (1998), MBT scores tend to be 15% lowers than post-FCI scores. College Physics students in this study had a mean MBT score that was only 5.5% lower than the post-FCI average, while the University Physics students had a mean MBT score that was 17.7% lower than the post-FCI average. The combined mean score for the FCI was 49.3%, while the combined mean score for the MBT was 37.7%—a difference of 11.6%. It should be noted that Yasuda and Taniguchi (2013) determined that 2 of the 30 FCI questions were invalid, and found systemic errors suggesting further research on the validity of the FCI. Interestingly, Hake (1998) also noted systematic errors in his data at the time, but nonetheless attributed the stark differences in conceptual change between traditional (low-gain) and IE (high-gain) results to pedagogy.

Table 20

Force Concept Inventory (FCI) Results

Course	Pre-test *M(SD)*	Post-test *M(SD)*	Gain $\langle g \rangle$
College Physics	8.3(3.7)	11.8(3.1)	0.16
University Physics	13.3(7.3)	17.8(6.4)	0.27
Overall	10.8(6.4)	15.0(5.9)	0.21

The normalized gain $\langle g \rangle$ is calculated as the ratio of the pre-post test score difference, relative to the difference between a perfect score and the pre-test score—thereby excluding prior knowledge from the evaluation.

Table 21

Mechanics Baseline Test (MBT) Results

Course	Percent Score *M(SD)*
College Physics	33.8(11.0)
University Physics	41.5(16.4)
Overall	37.7(14.2)

Summary

Students in this study population were given several assessments—the PEP for personal epistemology, and the FCI and MBT for conceptual change. In all three cases, positive gains were made as described herein. The elements of thinking and reasoning in terms of the a priori theoretical coding definitions described in the Proposal, as well as in vivo coding, reveal patterns that could support theoretical advancement in terminology that is capable of lending clarity to models of conceptual and epistemological change. Belief development and the influence on belief change also contain the distinct patterns of thinking and reasoning suggested above, and thereby lend further support to a theoretical advance in the way that concepts, models, thinking, and reasoning are understood with respect to epistemological change, as well as general cognitive constructs.

The research questions were concerned with how students use MRS in their thinking and reasoning, and how the use of those MRS in thinking and reasoning influence epistemological change. The MRS used in this study were largely written and narrative discourse about curriculum content that is symbolic and diagrammatic. The process of coding for EoT led to the discovery that concepts are poorly defined within the framework of thinking as described by Paul and Elder (2008), but also with respect to conceptual change literature in general (Vosniadou, 2010). The pattern that emerged from the study data suggested that concepts come in several families whose properties specify different kinds of properties and relations. The ongoing process of memo-writing in parallel to coding activity produced a taxonomy of conceptual frameworks which unifies and answers the research questions in this study. Chapter 5 presents that finding along with theoretical and practical implications for continued research and ongoing practice.

One of the limitations in this study is the duration of time between the end of the analysis phase in weeks one through four of the course, and the exit interviews conducted during week sixteen. Moreover, the pre-test and post-test conditions occurred 15 weeks apart—spanning the first and last days of class prior to the week where exit interviews were conducted. Though the course content of weeks five through fifteen were fundamentally the same as the week four content in terms of structure and approach, none of the week five through fifteen activities were part of the analysis. However, the focus of the exit interview questions specified how the overall experience related to changes in thinking, reasoning, understanding, and personal epistemology. While there were some large-scale changes in personal epistemology as measured by the PEP, it is not clear which phase of the course was related to that change.

The student perception of the interview and journal questions that specify thinking and reasoning are potentially different than what the researcher perceives, as well as what the theoretical coding definitions prescribe. The coding scheme employed in this study aimed to provide unambiguous definitions that are dependent on speech patterns rather than the inference of the coder. Moreover, constant comparative analysis and memo bracketing of the researchers' opinions provide a backdrop for understanding these potential limitations of the data and its analysis.

Chapter 5: Summary, Conclusions, and Recommendations

Introduction

The purpose of this study was to address a long-standing gap in the personal epistemology literature concerning the resources and mechanisms for personal epistemological change by crafting a new theory that describes the connection between thinking and reasoning with MRS and epistemological change. Given the context of an IP classroom for the study, and the persistent efforts of researchers in the PER community to measure conceptual change in IP settings, this study also includes data on conceptual change and the possible connection between conceptual change and personal epistemology. Thinking and reasoning is required for both conceptual and epistemological change, but is poorly defined in the literature (Nimon, 2013; Peters, 2007). In order to remedy this situation, a streamlined definition of thinking and reasoning was adopted for the sake of coding source materials that matched the practice of Physics in general while also being consistent with current mainstream views in the literature.

The importance of a new and productive theory of learning that spans the fields of conceptual change and personal epistemology cannot be understated—especially in terms of the psychological constructs of thinking and reasoning. Good theories have a broad explanatory scope that is resilient enough to handle significant changes in context—such as the content domain, and the conventional representational systems that work therein. Though this study is focused on the practice of Physics in an IP setting, as well as the MRS that are used in that endeavor, a grounded theory explaining how that is done has significant potential for describing thinking and reasoning with MRS in general. The potential of such a theory has import to human and machine intelligence in terms of the structure of knowledge by means of thinking and reasoning processes that employ MRS. Such a theory would provide researchers with the necessary tools to construct educational content and assessments regardless of the type of representational system. The Cognitive Modeling Taxonomy of Conceptual Frameworks (CMTCF) offered herein not only presents a means by which to do this, but the theory of learning that it is positioned in attempts to link the biology of brain function to the cognitive and behavioral activities that lead to MRS artifacts.

The study was conducted in two IP classrooms at a rural community college in central Arizona during the fall semester of 2014. Twenty-nine students participated in the study; which consisted of observation of normal classroom activities with the curriculum at Central Arizona College, as well as well as several assessments including the PEP and the FCI. The goal of this qualitative grounded theory study is to determine the influence that multiple MRS have on IP students with respect to their conceptual frameworks and personal epistemology.

R_1: How do IP students use representational systems in their thinking and reasoning?

R_2: How does the use of MRS in the thinking and reasoning of IP students promote personal epistemological change?

This chapter presents a new theory of learning that connects the neural activity of the brain to the cognitive and behavioral processes that learners use in order to generate artifacts in MRS. The core elements of the TRU Learning Theory are definitions of the psychological constructs of thinking, reasoning, and understanding in terms of conceptual frameworks. The CMTCF was generated in response to emergent themes in the study data that indicated how students used and constructed concepts. Traditional definitions of concepts tend towards general abstract ideas, rather than the way that concepts relate to and build upon one another. The CMTCF defines these relationships in terms of the way that they correspond to conventional and theoretical methods for modeling in IP. Moreover, the CMTCF answers the need for clarity about what a concept actually is in light of the forty-year history of conceptual change research that has resisted defining the term (Vosniadou, 2010).

The remainder of this chapter is organized to present an overall summary of the study explaining the general topic and the importance of the study, as well as a summary of findings and conclusions—which include the introduction of a new theory of learning. Implications for future theoretical development and research trajectories are offered in concert with the practical implications of these study findings. Finally, recommendations for the pursuit of new research questions and new or enhanced practices are offered in conclusion.

Summary of the Study

It is not known how (a) thinking and reasoning with MRS occurs, and (b) how that sort of thinking and reasoning affects epistemological change in terms of mechanisms and processes—whether cognitive, behavioral, or social—in an IP classroom. The findings herein suggest that this is due to the fact that concepts and conceptual frameworks are poorly understood, and that this is the missing structure that conventional definitions of the term model tend to ignore. Beliefs about Physics either refer to or require multiple representational systems (MRS)—such as words, symbols, and pictures (Plotnitsky, 2012), and are situated within a social and collaborative learning environment. The way in which Introductory Physics (IP) students use MRS in their thinking and reasoning ultimately conveys to changing concepts and beliefs. How students think and reason with MRS, and then how that conveys to epistemological change was the goal of this study as described by the following research questions.

R_1: How do IP students use representational systems in their thinking and reasoning?

R_2: How does the use of MRS in the thinking and reasoning of IP students promote personal epistemological change?

Conceptual change and epistemological change are connected by the representational systems used by learners when deploying them in contexts that require modeling (Jonassen et al., 2005, Nersessian, 2010). Learning physics requires thinking and reasoning within a context for problem solving where beliefs about the world are regularly challenged (Lising & Elby, 2005). However, there is no clear definition of the terms thinking and reasoning (Nimon, 2013; Peters, 2007) even though scores of types of thinking are well attested within the literature—specifically with respect to this study: scientific thinking and reasoning within the context of learning physics (Coletta et al., 2007a, 2007b; Hake, 1998; Hestenes, 2010; Rosenberg, Lorenzo, & Mazur, 2006). Furthermore, the term concept is poorly defined at best (Vosniadou, 2010).

In an effort to answer the research questions directed at how students think and reason with MRS towards epistemological change, the fact that thinking and reasoning are poorly defined was not only confirmed by the analysis, but also that its content in terms of concepts is also poorly understood—which makes describing thinking and reasoning in terms of concepts vague at best. During the coding process, reflections by the researcher in the memos discovered that concepts are descriptive, categorical, or relational. This finding led to the construction of the Cognitive Modelling Taxonomy of Conceptual Frameworks, which serves to amplify the definition of thinking as the ability to construct a model by uncovering the conceptual structure of models themselves. The conventional definition of a model as any representation of structure (Hestenes, 2010) did nothing to distinguish what *structure* actually is, and therefore made the judging of what counts as a model as subjective as the person making the judgment. Moreover, if modelling and thinking or reasoning are to be coordinated in any way, a solid set of definitions for what these processes are and what their content must be is essential for theoretical advance in educational and psychological research. The remainder of chapter 5 is dedicated to exploring and explicating such an advance.

Summary of Findings and Conclusion

Epistemological change measured by the PEP instrument revealed a modest positive shift in composite PEP scores by means of dramatic shifts within and between the three dimensions of the PEP: rational, empirical, and metaphorical. Analysis of the study artifacts—journals, discussions, and exit interviews—reveal a consistent pattern of concept construction by means of thinking and reasoning as distinct processes capable of forming conceptual frameworks. Thinking and reasoning (as defined by TRU) are believed to be the mechanisms of epistemological change (belief development), whereas conceptual frameworks and the learning environment are believed to be epistemological resources upon which epistemic framing coordinates conceptual change with belief change. These conclusions are described below in reference to the research questions and the emergent themes from the analysis of study data.

The significance of these findings corresponds to a reasonable call for paradigm shifts in conceptual change and personal epistemology research, as well as human and machine learning. Conceptual change research has long been stifled by a persistent devotion to pre-post-test approaches that have yet to produce theoretical clarity (DiSessa, 2010). Personal epistemology research has suffered a similar fate at the hands of models and theories that lack clarity, and assessment methods that fail to produce consistent results. According to Clement (2010), the mechanisms of conceptual change are not known because the definition of a model is vague. Bendixen (2012) echoes the assessment given by Clement (2010) and diSessa (2010) concerning conceptual change when describing the state of epistemological change research having little to no data on the processes and mechanisms of this phenomenon. The call for qualitative studies investigating the contextual factors of epistemological change has persisted from Hofer and Pintrich (1997) through Bendixen (2012). This study sought to fill those gaps in the literature, and has thus produced a new theory of learning—the TRU Learning Theory—that brings them all together under the structure of the CMTCF, described herein.

Research Question 1.

R_1: How do IP students use representational systems in their thinking and reasoning?

The Physics and reality classroom event revealed patterns in thinking and reasoning that were limited to written and narrative representational systems. The nature of the questions in this event did not warrant the use of graphical or diagrammatic representational systems because the activity demanded only narrative and written responses in natural language, and therefore none were observed. However, intricate patterns were obtained in the qualitative analysis revealing the kinds of interactions that lead to belief change and the types of narratives that promote those changes, as well as the cognitive resources that support them.

The largest shifts in thinking and reasoning occurred in terms of the individual and group point of view (POV) expressed by students in journal entries and group discussions or interviews. Epistemological changes measured by the PEP instrument indicate large variations in one or more epistemological dimensions (rational, metaphorical, or empirical) in concert with the treatment under study. It is unsurprising that the content of beliefs is in some way conceptual, and therefore the shifts in concept usage observed in the coding of study artifacts also describes in some way the underlying structure of thinking and reasoning.

Theme 1: distinctions (thinking). The very nature of the questions posed in this activity—What is Physics? What is Reality? Is Physics Reality?—seem to force students to evaluate not only their own beliefs, but also the beliefs of others in the process of compelling them to define their concepts. As students consider the questions, they use inferential (if-then) reasoning (coded under Coordinations) in the comparison of their own views with the views of others—which forces a coordination of existing concepts and the possible assimilation/accommodation of concepts provided by other students engaged in the same debate. Reflection on ones' own beliefs requires the use of metacognitive control, while the consideration other perspectives requires a process of critical listening followed by dialectical thinking about that content. Subsequent interpretations (an EoT) and assimilations/accommodations of new information (another EoT) present an organic opportunity for thinking and reasoning because of the nature of the questions and the learning habitat.

This study positioned the construct of thinking in two ways by using the EoT by Paul and Elder (2008), and a synthesis of that structure with the general practice of science in terms of modelling. The proposed coding scheme of thinking as the ability to construct a model, and reasoning as the ability to relate one or models, was intended to provide a better fit to scientific thinking and reasoning in parallel with the EoT. A decision to delay coding by this scheme was made in an effort to allow the in vivo coding and the a priori theoretical coding in terms of the EoT to flow naturally in the first phase of data analysis. During that process the discovery was made that the content of EoT Concepts varies so widely, that coding for thinking or reasoning by the proposed synthetic scheme was not possible without a clear definition of what concepts are, and how they are coordinated into a model. Some of the content coded as concepts presented in forms that dealt strictly with categorical declarations versus relational ones. This finding led to the taxonomy offered below. According to Vosniadou (2010), conceptual change researchers have historically tended to avoid defining the term concept—preferring rather to position them as something that changes within a larger theoretical framework of cognition. Moreover, the definition of model as any representation of structure was found to be lacking sufficient clarity, and thus the following taxonomy of conceptual frameworks was created.

The Cognitive Modelling Taxonomy of Conceptual Frameworks (CMTCF). Concepts are defined as one or more descriptive distinctions (metrics) about something. There are two families of concepts leading up to the collection of concepts that comprise the structure of a model. Pericepts are concepts that have the capacity to categorize or classify other concepts, whereas Metacepts serve to define relations or relationships between other concepts because some concepts are *about* other concepts rather than being *about* something. Modelling concepts are simply the coordination of multiple concepts that represent the structure of complex ideas, and in this way, the term modelling becomes more precise by specifying the resource for structure.

The way that concepts are coordinated (conceptual frameworks) is the *structure* that the conventional definition of model refers to when defining model as any representation of structure. Representational systems (words, pictures, symbols, diagrams, etc.) are the only ways to communicate the content of a model—which is entirely in the form of concepts whose construction and coordination require, and thus define, the construct that we call thinking. The following definitions are offered in establishment of the proposed conceptual framework.

Concept. One or more descriptive (metric) distinctions about something. For example, bananas are yellow provides the metric yellow as describing a property of bananas. The statement: stones are hard uses the term hard in the same way.

Pericepts. Concepts that serve to categorize or classify other concepts. This family of concepts includes Supercepts and Subcepts, defined below.

Supercept. Categorical concepts with capacity to group other concepts. For example, the statement: sticks and stones are things uses the concept of thing as a grouping concept for the class of things known as sticks and stones.

Subcept. Concepts that form classes within, or under, more general concepts such as Supercepts. For example, the statement: apples and oranges are fruit uses the concepts of apples and oranges as classes within the categorical concept (Supercept) of fruit.

Metacepts. Concepts that serve to define a relation or a relationship on or between other concepts. This family of concepts includes Hypocepts and Hypercepts, defined below.

Hypocept. Relational concepts about other concepts. For example, the statement: sticks are not stones uses the relational concept of not the same as a way to encode for the lack of equality between sticks and stones. The statement: this is greater than that uses the relational concept of greater than to encode for how much larger this is than that.

Hypercept. Concepts about other concepts encoded in the form of a relationship. For example, the statement: there are three groups of two stones uses the concepts of numbers as a way to encode for the group structure of the collection in terms of what can be counted.

Modelling Concepts. The coordination of concepts by means of other concepts, which in turn represent the structure of complex ideas by creating a new concept. This family of concepts includes the and the Nomocept, as defined below. The primary differences between a Multicept and a Nomocept is the manner by which Hypercepts are joined, and the descriptive scope of the Hypercepts in relationship.

Multicept. The encoding of Hypercepts coordinated by a Hypocept. For example, the statement: three groups of two stones is equivalent to two groups of three stones uses the hypocept of equivalent to as a way to coordinate the invariance under regrouping that is evident in the fact that regardless of how you group six stones—2 groups of 3, or 3 groups of 2—the sum total remains the same.

Nomocept. The coordination of Hypercepts through a reasoning process. For example, the statement: a change in position always requires a change in time uses an inferential reasoning process in order to connect the two change quantity Hypercepts. The term Nomocept was chosen because the Greek word *nomos* refers to law, and scientific laws are simply empirically familiar regularities. The statement in this example is an undeniably true description of motion for any object in a Newtonian world.

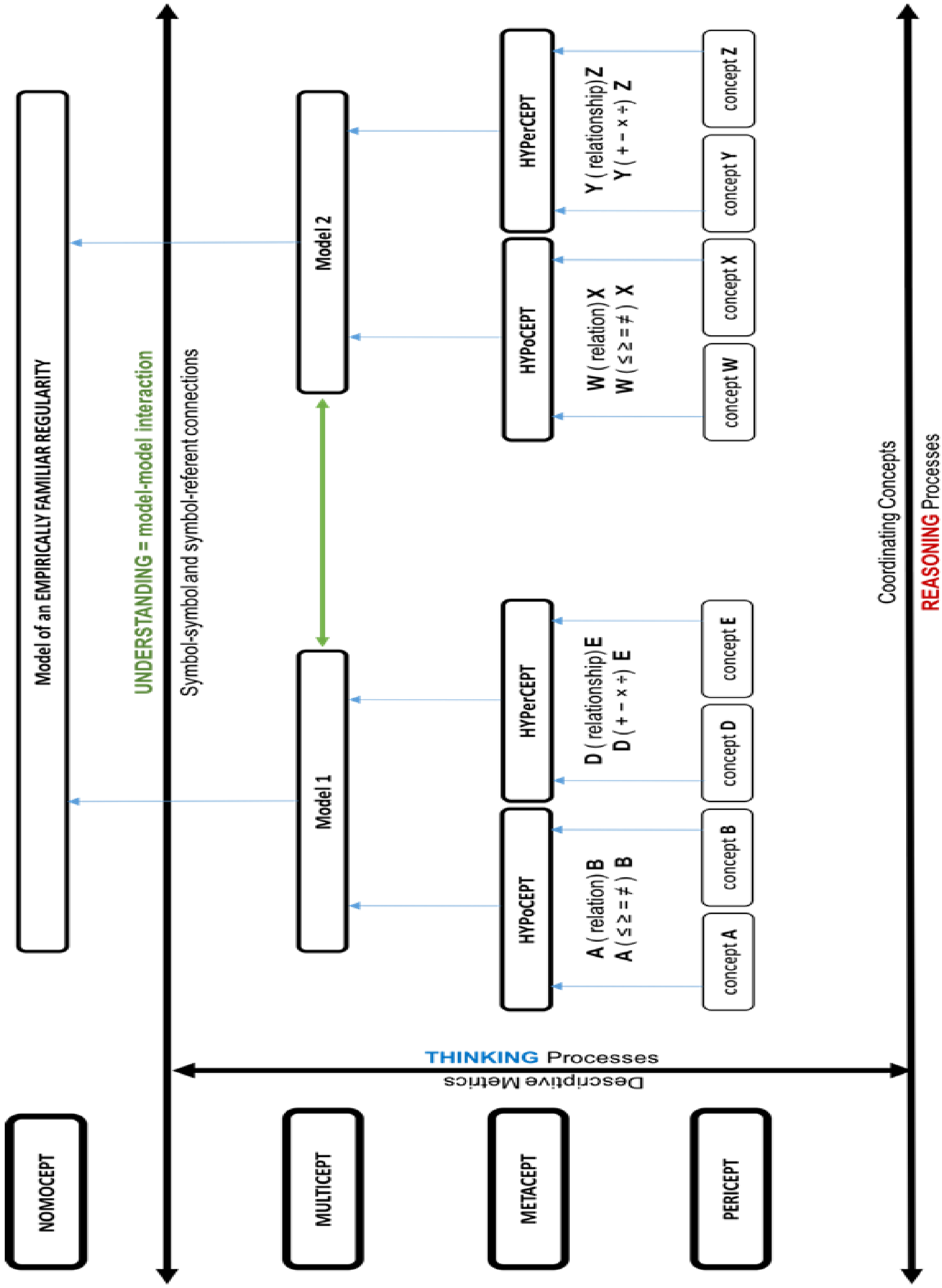

Figure 19. Cognitive Modeling Taxonomy of Conceptual Frameworks - Processes.

The Cognitive Modeling Taxonomy of Conceptual Frameworks (CMTCF) shown above in Figure 19 illustrates the progression of Thinking as a construct that advance vertically from basic concepts towards complex conceptual frameworks. Reasoning processes occur horizontally in the form of coordinating concepts at all levels of thinking. Thinking and reasoning are thus fundamentally different, though inextricably linked. Understanding is possible only at the level where models interact with other models in terms of the symbol-to-symbol and symbol-to-referent correspondence—which ultimately entails reasoning between multiple contexts via MRS. The Nomocept is the pinnacle of the taxonomy, and represents the generalization of law-like models based on empirically familiar regularities (EFR). It should be noted that top-down thinking from a law is also permitted in this taxonomy in the case where the EFR is already known by the modeler. Law-like understanding can be parsed from the top-down, or built from the bottom-up in manners consistent with top-down and bottom-up theories of thinking and reasoning.

Given that thinking was initially defined as the ability to construct a model, and that a model is simply any representation of structure (Hestenes, 2010), this taxonomy proposes that multicepts are the structure of models, and that the construction of a model under this framework is evidence of thinking. If the content of thinking is model construction, and model construction is concept coordination, then the coordination of models is naturally something other than thinking—or at least a form of thinking on a higher level that what has been described herein. The EoT provided by Paul and Elder (2008) define reasoning as just another kind of thinking; however, there is no clear means by which to distinguish thinking from reasoning under that model. The coding scheme for reasoning defined as the ability to relate multiple models ended up matching the patterns found in the study data, and is therefore proposed as the new definition of that construct.

Theme 2: coordination's (reasoning). Students engaged in the metacognitive control associated with considering their own views and the views of others are compelled to sort and organize the pre-existing concepts that they have in light of new ones exposed in the group interactions. Initially, this is handled by trying to defend existing views, but also by attempting to assimilate new ideas when found to be superior to old ones. When the Distinctions that students made are compared to the Coordinations in terms of how the EoT comprise either cognitive activity (see Figure 6), the results indicate a shift away from Group or Individual POV simultaneous with an increase in the use of Information, Interpretation, Assumptions, and Questions. The use of Concepts remains largely the same. The content of thinking and reasoning in terms of the EOT is largely the same in terms of the individual elements of thought as described by Paul and Elder (2008); however, in addition to the varied proportions of EoT usage, there are additional ways in which those collections of EoT are coordinated. Those additional methods of coordination come largely in the form of if-then statements that are classically understood as inferential reasoning, as well as knowledge justification statements that use the term because to link up beliefs with models and concepts.

This shift is one way to distinguish the cognitive activity of thinking from reasoning in terms of how model/concept creation arises from the distinction-making process (thinking), and the coordination of multiple models/concepts relationally (reasoning). The findings offered in support of this pattern are consistent with the definitions of thinking and reasoning offered in chapter 2 as a way to encapsulate the EoT by Paul and Elder (2008) within the practice of science in general. Though Distinctions and Coordinations employ the same set of EoT, they do so in varying and consistent proportions—thereby indicating on one level that reasoning is in fact another type of thinking, but also allowing for a means to distinguish that shift in terms of cognitive processes other than distinction-making. For example, the sub-codes of the Coordination theme are IF-THEN, Related Things, Collections, and I Believe Because. In all cases, the cognitive agent is forming relationships between previously made distinctions, and/or existing Coordinations—in other words, reasoning involves the formation of relationships between things or relationships, which affirms the definition of reasoning offered by the author: reasoning is the ability to relate multiple models.

The simple difference between thinking and reasoning is the difference between model construction and model-to-model interaction. The content of thinking and reasoning is entirely models, and models are simply coordinations of concepts. However, thinking is the process of model construction in terms of concepts, whereas reasoning is the process of forming model relations and relationships. Both processes rely fundamentally on concepts since relational and relationship concepts are the *glue* that makes model construction possible.

Given the Cognitive Modelling Taxonomy of Conceptual Frameworks (CMTCF) offered herein, it is now possible to accept the definition of reasoning as the ability to relate multiple models when model construction is understood as evidence of thinking. Thinking and reasoning are thus connected in terms of what they operate on or within. The noticeable transitions in magnitude and frequency of EoT usage between Distinctions (container for descriptive metrics) and Coordinations (relations between descriptive metrics) indicate that thinking and reasoning are in fact distinct cognitive constructs deserving of separate consideration in future research.

Research Question 2.

R_2: How does the use of MRS in the thinking and reasoning of IP students promote personal epistemological change?

Theme 1: belief development. The findings herein describe patterns of thinking and reasoning about the content and the process of coming to a set of beliefs concerning the nature of physics, mathematic, science, reality, thinking, reasoning, understanding, and motion. The content of thinking in terms of concepts, and the coordination of families of concepts through inferential reasoning and knowledge justification suggest that the use of natural language in either written or narrative form is essential to producing epistemological change. Qualitative findings described in chapter 4 illustrate that change explicitly, and the quantitative results of the PEP assessment support the import of those findings in terms of the epistemological dimensions of rational, empirical, and metaphorical measured by the PEP. The PEP dimensions are more or less dispositions towards thinking or reasoning about the world, and therefore expand the scope of inquiry about the types of thinking and reasoning that produce epistemological change.

In the second half of the activity set under study, students were repeatedly asked to reflect on how their thinking, reasoning, and understanding had changed as a result of the activities conducted thus far. Most participants did not think that their beliefs had changed; however, most participants did think that the way that they understand their beliefs had changed. Given the large-scale changes in the PEP dimensions among most of the participants, this suggests that the curriculum under study is structure well for epistemological change. In general, this curriculum is collaborative and reflective with intensive writing and discussion opportunities. This sort of learning community makes metacognitive and critical listening demands about beliefs, and therefore suggests that curriculum content and/or pedagogical engagement are resources for epistemological change.

The answer to the how question of thinking and reasoning with MRS has now been answered in terms of the conceptual frameworks described by the CMTCF. Moreover, if thinking is the ability to construct a model, and models are the coordination of different families of concepts, then to the degree that beliefs have conceptual content, the CMTCF describes epistemological change. No matter how vague or precise ones' definition of thinking might be, it is difficult to imagine that it is devoid of conceptual content. The structure of beliefs can now be analyzed in terms of not only its conceptual content, but also whether or not the structure of those beliefs is limited to mere thinking about a single model, or reasoning between multiple models.

Theme 2: Thinking-Reasoning-Understanding (TRU) Claims. Students made claims about whether or not their thinking, reasoning, or understanding had changed after attempting to define understanding. Understanding was typically defined as the ability to explain what you know to another person. Memo activity during the Learning the Language activity questioned whether or not understanding is context-dependent because the nature of this activity required students to reason between MRS in order to obtain a meaningful and coherent interpretation. The construct of Understanding was thus defined as the ability to sustain Reasoning across a shift in context. Based on the sum total of these findings, the author suggests a new theory of learning called the TRU Learning Theory, where TRU is an acronym for Think-Reason-Understand.

Introduction and background to the TRU Learning Theory. The Hebbian Principle of neurons that fire together wire together is sufficient for defining learning as the coordination of the activation of multiple regions of the brain. Various representational systems (RS) have the ability to activate different regions of the brain. Through these multiple representational systems (MRS), humans encode for meaning in an attempt to build models of the world with capacity to represent the structure as they perceive it.

The cognitive activities of thinking and reasoning are often conflated with one another or defined in self-referential manners. The term model is most often defined as any representation of structure, where structure indicates the relations between things being modelled. Concepts are inevitably part of this cognitive-behavioral process, but they are more vaguely defined than models. The following definitions of the TRU constructs are given below in term of concept and conceptual frameworks as defined by the CMTCF.

TRU Theoretical Statement. The TRU Learning Theory asserts that multiple representation systems (MRS) encode for meaning by coordinating concepts in a manner that activate multiple regions of the brain, and thus form conceptual frameworks in accordance with the Hebbian Principle.

Definitions

Thinking. The ability to construct a concept. The most basic concept besides mere recognition of a thing is a concept that provides a descriptive metric for the thing in question. Along this line of thinking, the concepts that serve to classify and categorize allow the cognitive agent to sort and organize worldly objects and events.

Reasoning. The ability to construct a conceptual framework. The Modeling Concepts of the Multicept and the Nomocept are conceptual frameworks that function as models. Multicepts are constructed on the basis of relations and relationships, whereas the Nomocept is borne out of a reasoning process such as inferential reasoning.

Understanding. The ability to relate conceptual frameworks. The use of MRS allows for the encoding of a model in multiple *languages*—so to speak. The degree to which a modeler can form symbol-to-symbol and symbol-to-referent connection both within and between MRS is the degree to which the models are understood within and between contexts.

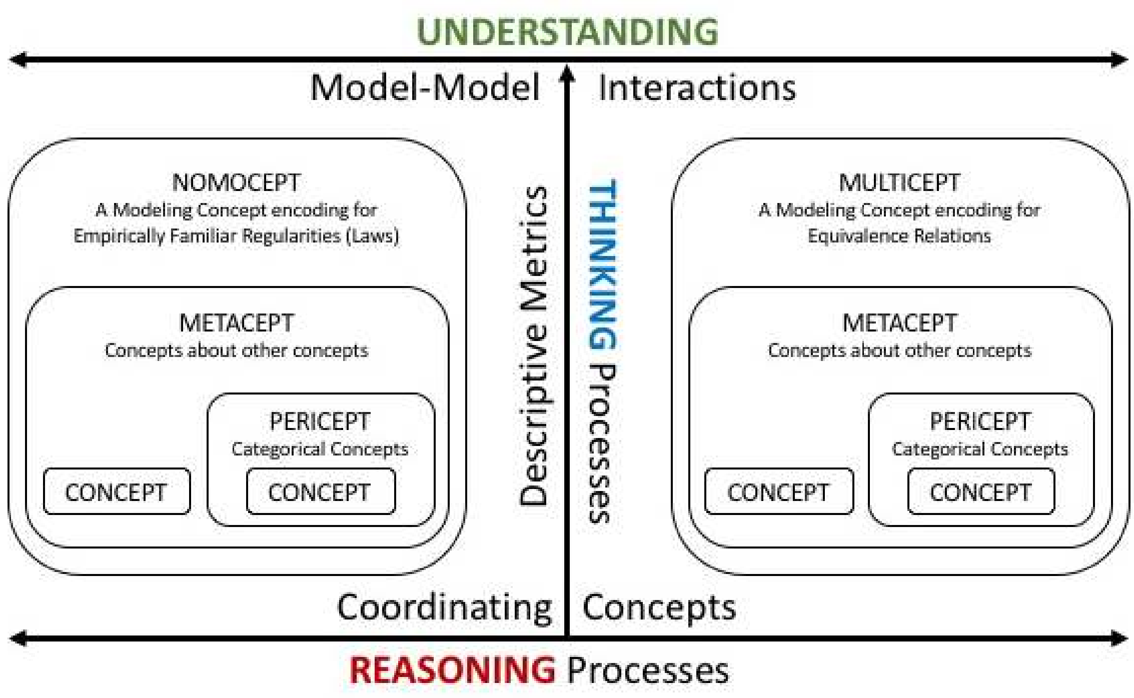

Figure 20. Cognitive Modeling Taxonomy of Conceptual Frameworks - Collections.

Example from Physics Using the CMTCF. Consider the law-like statement: a change in the position [of an object] always requires a change in time. From an observational point of view, this is an Empirically Familiar Regularity (EFR) in the large-scale world of objects that can be seen. Objections to this rule (law) deny physical reality. Position and time are basic concepts about features of the world where objects reside, and the concept that there can be a change in either one is properly described under the CMTCF as a **hypercept**: concepts about other concepts encoded in the form of a relationship. In this case, both a change in time and a change in position use the concept of relational concept of change on the basic concepts of position in time in order to form new concepts that are about position and time.

The phrase “always requires” encodes for an inferential connection between these two change quantities that fundamentally places the two concepts in a relationship that obeys the law (*nomos*) previously given—that a change in position always requires a change in time. This conceptual connection is a **nomocept** because it serves to define the law-like connection (empirically familiar regularity) between the two **hypercepts** on position and time.

$$\underbrace{a\ \overbrace{change\ in\ \underbrace{position}_{concept}}^{hypercept}\ \underbrace{always\ requires}_{\substack{reasoning\\ process}}\ a\ \overbrace{change\ in\ \underbrace{time}_{concept}}^{hypercept}}_{nomocept}.$$

Figure 21. CMTCF example 1: first zeroth law of motion.

One way to encode for this model is to write the equation $\Delta s = v\Delta t$, which specifies speed as the physical connection between space and time. Speed is not a thing, and neither was the relational concept of “always requires”—hence the conceptual connection as a metacept (hypercept) retains its basic property of *about-ness* as a derived quantity in the physical world. Speed is about coordinated changes rather than a substance upon which a categorical statement can find grounding, or an object upon which a descriptive metric can be formed.

The Cognitive Modelling approach requires that an axiom should encode for what the law (nomocept) describes. The following arithmetic illustrates how this is done using the quotient operation as a way to encode for the "always requires" type of metacept.

Table 22

Cognitive Modeling Approach to Axiom Development

$\Delta s = \Delta s \qquad \Delta t = \Delta t$	Identity Multicept. It is undeniably true that something is identical to itself. It is important to realize that though a position can be identified in the real world, a change in position, and/or a change in time, is a metacept about such worldly things.
$\frac{\Delta t}{\Delta t} = 1$	Quotient Identity Multicept. Since changes in time are independent of the change in position of the object, we can use this fancy form of one (*ffoo*) as a multiplier that has capacity to preserve the identity on their dependent multicepts, while making a new relation feasible.
$\Delta s = \Delta s \frac{\Delta t}{\Delta t}$	Preservation of Identity Multicept using a fancy form of one (*ffoo*). The axiom DOES NOT yet encode for what the law describes because the two quantities do not stand in a binding (quotient) relationship with one another.
$\Delta s = \frac{\Delta s}{\Delta t} \Delta t$	Letting the axiom encode for what the law describes by using the quotient relationship symbol as a way to encode for "always requires". In this case, "always requires" is synonymous with the concept of "per". Moreover, standard arithmetic permits the shift.
$\Delta s = v \Delta t$	Creating a new concept and encoding for it with a new symbol. The symbol-referent connection is to a hypercept—which is a type of metacept, and metacepts are about something rather than being ontologically something.

This vector diagram (Figure 22) encodes for the axiom as well as the narrative law by illustrating with geometric objects all of the concepts **<u>except</u>** for a change in time. The quotient of change in position relative to a change in time, scales the change in position length by some amount. Such a conceptual synonym is able to model some of the parts of the original Multicept, but not all. Moreover, it has capacity to encode for direction in a way that the natural language model cannot.

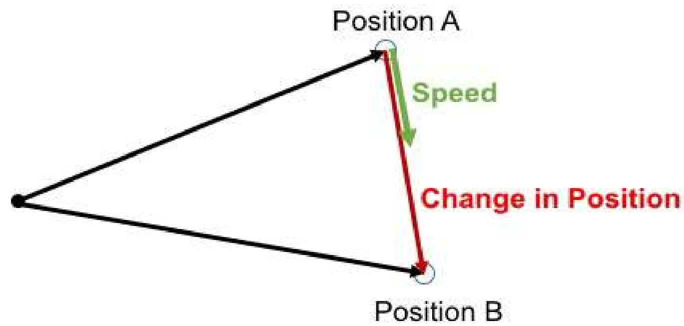

Figure 22. Vector diagrammatic model of the First Zeroth Law.

The ability to coordinate multiple models—such as natural and diagrammatic—lends clarity to both models because each RS has a different capacity for encoding meaning. An additional diagram is needed in order to fully coordinate the first diagram with the natural language law, or its axiom.

In this diagram, the connection between space and time can be *seen*. The slope of the line is a constant value whose magnitude is dependent on how wide the time interval is in comparison to the position interval. In this way, the diagrammatic RS encodes—or potentially encodes—for the magnitude of the speed relative to the primary change quantity (position) that defines it relative to time. However, this graphical RS does not encode for direction, whereas the vector diagrammatic RS does. For these reasons, the need for RS other than just the natural or the symbolic is needed in order to generate a comprehensive model that is the result of multiple model-to-model interactions.

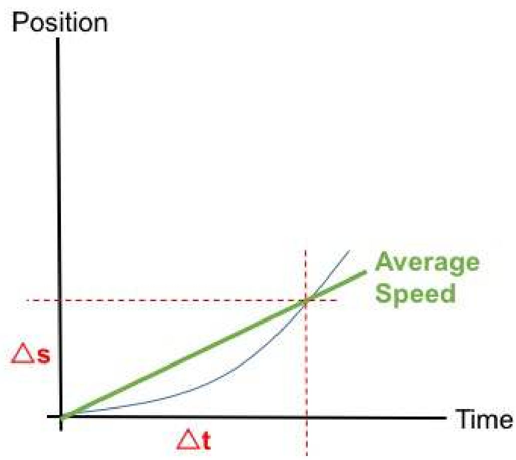

Figure 23. Graphical model of the First Zeroth Law.

Reasoning = model-to-model interaction. In the same way that a change in position requires a change in time, so does a change in speed.

$$\underbrace{a\ \overbrace{change\ in\ \underbrace{speed}_{concept}}^{hypercept}\ \underbrace{always\ requires}_{reasoning\ process}\ a\ \overbrace{change\ in\ \underbrace{time}_{concept}}^{hypercept}\ .}_{nomocept}$$

Figure 24. CMTCF Example 2: Second Zeroth Law of Motion.

The Cognitive Modeling approach permits the construction of an axiom that encodes symbolically what the law above describes—or $\Delta v = a\Delta t$.

$$\underbrace{\overbrace{\Delta v}^{hypercept} \underbrace{=}_{hypocept} \overbrace{\underbrace{a}_{concept} \overbrace{\Delta t}^{hypercept}}^{hypercept}}_{multicept}$$

Figure 25. CMTCF example 3: Second Zeroth Law axiom.

This axiom ends up creating a new concept conventionally known as acceleration. In one sense, it as though the reasoning process of "always requires" became an equivalence relationship for the new construct. This highlights the transformative capacity or RS to encode for and subsequently create new concepts. However, the new conceptual creation tends to be be more or less explicit depending on the RS context. For example, the natural language of *a change in speed always requires a change in time* does not explicitly provide one with the concept of acceleration—much less the construct. However, the symbolic approach lends the modeler an opportunity to pick/create a name label for the new concept—which in this case is a relationship, or Hypercept.

The transition between natural language and symbolic language in the acceleration law given above retained the elements on the outer edges (change in speed and time) as Hypercepts across both RS. These are essentially RS synonyms. The reasoning process of *always requires* is in some way equivalent to the combination of an equivalence relation (hypocept) and the new construct of acceleration labeled *a.* Moreover, a new Hypercept connection serves to link the equivalence relation and the new construct within the original conceptual framework. The empirically familiar regularity that supports the notion of *this always requires that* results in an equivalence relation connecting the original concepts via a new and derived concept. The mathematical equivalent of the universal quantifier on constraint (*always requires*) is an equivalence relation definition via a new concept.

Perhaps one translation of the symbols back to words is that a change in speed *is the same but not the same* as the connection between acceleration and time. The notion of *the same but not the same* is what the equivalence relation demands in the absence of an identity. Another possible translation might that a change in speed is defined to be the connection between acceleration and time.

Predictions.

1. Two or more RS are required for building a physical network of knowledge within the human brain.

2. There is a causal connection between the cognitive content of a model as defined herein, and the behavioral artifacts that present in the form of MRS.

3. Understanding is contingent on one or more diagrammatic RS within the family of MRS used by a modeler. In other words, the ability to make symbol-symbol and symbol-referent connections within and between RS is the key to understanding.

4. Optimal learning achievement is contingent on a family of MRS that include symbolic, diagrammatic, and natural language RS.

Suggestions for TRU Learning Theory use

1. Obtain frequencies for every attempt to produce concepts and models, and then compare that to the frequency of attempted concepts and models that have logical and/or conventional merit.

2. Log the frequency of RS used—such as natural, symbolic, diagrammatic, etc.—and continuously compare relative to the evolution of conceptual frameworks within persons or groups.

3. Build curriculum and assessments from the ground up, using the CMTCF as a guide. This is likely a paradigm shift away from the dominance of pre-post-test strategies towards a qualitative constant comparative analysis.

4. Use as a measure of intelligence in terms of the creative output of the individual relative to conventional merit, as well as RS fluency within a cultural context.

5. Use as a standard for machine learning and artificial intelligence. Current approaches to machine learning are consistent with the findings herein, but fail to specify the process in sufficient detail, or provide coherence in terms of the basic constructs described herein.

These findings, and the TRU Learning Theory described herein, provide a clear path for future analyses of MRS in terms of the conceptual content, and the means by which those concepts are constructed. This applies to all learning—human or otherwise. Given that personal beliefs and the cognitive processes for forming those beliefs are described in terms of concepts and conceptual frameworks, the TRU Learning Theory simultaneously answers the call by both conceptual change research and epistemological change research fields for greater theoretical clarity as it pertains to terminology, mechanisms, and resources.

Implications

Paul and Elder (2008) suggested the process of *thinking* is what generates the reasons that the process of *reasoning* then bases its conclusions on. Holyoak and Morrison (2012) defined thinking as transformations of mental representations for the sake of goal-directed modeling. The definition of model as any representation of structure (Hestenes, 2010) is surely true, but provides no clarity with which to judge the relative merit of any model. The CMTCF solves all of the problems in clarity described in the literature review by distinguishing thinking from reasoning in terms of their conceptual content and coordination. A general definition for the constructs of thinking and reasoning in terms of concepts has widespread implication for research in general psychology, philosophy, personal epistemology, conceptual change, human learning, machine learning, and intelligence.

Theoretical implications. The changes in theory that the TRU Learning Theory might impose are more likely to be affordances in clarity rather than content. The current definitions of constructs like thinking and reasoning are merely vague or circular. The general use of the term concept boils down to any idea that an agent can have, and the field of conceptual change research has avoided defining what concepts actually are

(Vosniadou, 2010). In each case, the present lack of clarity is still true to some degree; however, measuring change on constructs so poorly defined may prove to have been less than useful.

In many ways, the CMTCF is the missing link in conceptual change research because it precisely defines what concepts are, as well as how the coordination of concepts corresponds to thinking, reasoning, and understanding. Moreover, conceptual change research has suffered from a snapshot view of conceptual change in the form of pre-post-test strategies instead of longitudinal qualitative ones (diSessa, 2010). The degree to which concepts correspond to beliefs, and conceptual change corresponds to conceptual frameworks, determines the connection that exists between the research fields of conceptual change and personal epistemology. TRU Learning specifies the mechanisms for conceptual change by defining how thinking and reasoning correspond to conceptual frameworks. The primary resource for conceptual change is the use of MRS that are situated within various domains of knowledge and inquiry, as well as social structure—which Bodin (2012) describes as epistemological framing activating a network of epistemological resources. Bing and Reddish (2012) defined epistemological resources as social, affective, and artifact-based, whereas Bodin (2012) described the epistemological framing as dealing with the way in which knowledge and beliefs are constructed. The CMTCF could then lend precision to the question of epistemological framing in terms of how conceptual frameworks structure both knowledge and beliefs, as well as the interaction that exists between the social aspects of a learning environment and the MRS used therein to produce artifacts that encode for concepts and models.

Human and machine learning differ on many levels; but with respect to the elements of this study, one clear distinction is the ability of humans to form beliefs versus the ability of a machine to do the same. The correspondence between human thinking and reasoning versus machine thinking and reasoning within the context of model and knowledge construction is foundational to the potential research questions of (a) what is a belief, and (b) what do machines believe? This sort of trajectory in research could also touch on issues in the difference between mind and brain, as well as consciousness.

Practical implications. Each of the elements of the TRU Learning theory—concepts, models, etc.—can be counted in terms of their construction and their conventional efficacy in terms of how naïve or sophisticated they are judged to be by an expert. Moreover, within each of these frequencies there is ample opportunity to capture various types of each construct in both qualitative and quantitative ways. As shown in the prior section, the TRU Learning Theory has the capacity to fully describe the conceptual framework and cognitive processes required to fully understand motion—the most basic construct in Physics. Moreover, the example given utilized four different representational systems in the process—natural, symbolic, diagrammatic, and graphical. Furthermore, the Cognitive Modeling approach provides a modeling method for converting words into symbols that equate to conventional models. The amount of conceptual change that can be tracked and measured under such a paradigm holds great promise for education reform within Physics. The CMTCF is general enough to apply to any structured body of knowledge regardless of context, so long as conventional representational systems are productive in expressing the conceptual content of that domain. Therefore, the TRU Learning Theory is a general theory of learning due to its wide application in terms of

MRS, as well as the hypothesis that multiple regions of the brain are activated and coordinated by the use of MRS.

Future implications. The TRU Learning Theory is in some ways a complete paradigm shift away from the status-quo of pre-post-test assessments of conceptual change (diSessa, 2010), by answering the demand in personal epistemology research to explain how learners develop conceptual knowledge about the world and how that conceptual knowledge influences belief (Hofer, 2012). It is the mechanisms and processes of epistemological change, as well as the contextual factors of the same, that have eluded personal epistemology researchers for the last 40 years (Bendixen, 2012). These two fields are more deeply connected than anyone could have realized in the absence of a clear set of definitions for all of the critical constructs therein—namely, concepts and models.

If the Hebbian principle of neurons that fire together wire together is true, then human learning could be defined as the coordination of the activation of multiple regions of the brain. MRS have capacity to activate various regions of the brain, and thus influence learning in this fashion. The connection between MRS and regions of interest (ROI) in the brain have potential import for understanding how brain function and conceptual change are structured. The parallels between machine learning and human learning are now accessible in terms of the ways in which knowledge content is encoded.

Intelligence research is no better off than the aforementioned fields with respect to understanding how its conceptual content corresponds to the types of thinking and reasoning that intelligence tests are supposed to measure. A great deal of clarity is possible with the aid the CMTCF when it comes to defining intelligence, and therefore another potential paradigm shift is possible in both human and machine intelligence research. In many ways, the CMTCF portion of the TRU Learning Theory is akin to discovering that atomic structure of matter. It would be presumptuous to extend the import of this theory any further than that atomic structure metaphor, as the aforementioned paradigm shifts are more likely to provide a deeper set of advances in theory and practice.

Strengths and weaknesses. The strength of this study is rooted in the logical consistency of the TRU Learning Theory that was produced through an extensive analysis of the data provided by the study population. Multiple coding schemes in multiple data types converge on the same result that thinking and reasoning are distinct cognitive processes dealing with aspects of the knowledge construction process. The key aspect of the TRU Learning Theory that coordinates knowledge construction with the constructs of thinking and reasoning is the CMTCF—which defines concepts and situates them in conceptual frameworks built by the cognitive mechanism of thinking and reasoning. Moreover, the CMTCF is well-suited for modeling Physics in general by virtue of it focus on models and model construction, as well as positioning the construction of law-like models as the paragon of the taxonomy. Two potential weaknesses in the study are (a) the long span of time between the series of activities studied and the post-test condition for the PEP, and (b) the potential misuse of the a priori theoretical codes for the EoT by Paul and Elder (2008). However, one of the problems that arose in using the Concepts EoT code gave rise to the realization that Concepts come in several different types, and that they are coordinated with one another in ways that demand more than one distinction (coding option). The potential to misuse the EoT codes did exist; however, the in vivo coding process ameliorated this, and led directly to the author-defined constructs of thinking and reasoning—which are fundamental to the conceptual framework process in the CMTCF.

Recommendations

The TRU Learning Theory is an ambitious proposal with far-reaching implications for research and practice within multiple fields. The learning sciences span both human and machine learning, and therefore psychology, neuroscience, and computer science. New opportunities to refine theoretical approaches through use of the CMTCF, as well as common metrics for thinking, reasoning, and understanding, serve to present a grand opportunity for interdisciplinary collaborations that could lend clarity to fundamental research questions in all applicable fields—such as what is thinking, what do or can machines believe, etc. The following recommendations attempt to capture those opportunities in a clear and concise manner.

Recommendations for future research.

1. The CMTCF is the starting point for analyzing any future research on conceptual change. In order to know what conceptual change actually is, it is crucial to have a clear definition of concept first. Based on findings therein, a complete reevaluation of instruments designed to measure conceptual change is warranted in both qualitative and quantitative modes.

2. The key elements of the TRU Learning Theory are based on the CMTCF. Research on thinking and reasoning would therefore need to retool in terms of the structure of models—a paradigm-shift for any field of inquiry that purports to measure or define thinking and reasoning.

3. Human and machine learning are contingent on the ability of an agent to construct a model, and therefore have and coordinate concepts. Both human and machine intelligence are linked to what either type of agent can learn, and thus all areas of intelligence research could benefit from a more precise definition of concepts, models, thinking and reasoning. How do different measures of intelligence correspond to the conceptual frameworks described by the CMTCF?

4. Neurons that fire together wire together, and these sorts of results exist because of behavior in learning environments. The features of those learning environments are rich with social and collaborative properties, as well as MRS. Extensive research capable of tracking and coordinating these properties of the teaching and learning enterprise is needed. Mixed method research that includes direct measurements of brain activity with respect to the presence of this set of environmental properties is crucial.

5. Students are capable of producing models, some of which are conventional. The frequencies of both, as well as the RS employed in the process are needed for determining the optimal set of resources required for optimal learning within any discipline. Moreover, the varied types of reasoning—such as inferential, analogical, metaphorical, proportional, etc.—must be tracked in exhaustive detail in order to discover how those cognitive patterns correspond to conceptual frameworks.

6. How do conceptual frameworks correspond to personal epistemology in terms of basic conceptual content? In other words, how many descriptive metrics are sufficient for conceptual change? Is there a maximum number beyond which thinking and reasoning are impaired? What is the relationship between conceptual change and epistemological change?

7. How do the parts of speech correspond with the cognitive operations described by the CMTCF? Adjectives describe categorical features of concepts, and are thus related to the Pericept construct. Adverbs and conjunctions describe relations and relationships, and are therefore suitable for use as linguistic forms of Metacepts. The ability to digitally automate the search for parts of speech equates in part to an ability to detect thinking and reasoning, and in this way, the CMTCF can be used for analysis of natural language artifacts.

Recommendations for future practice. In terms of educational practice—within the context of this study—it is the learning habitat and the curricular content that drive epistemological change. The learning habitat is a student-centered community seeking consensus through collaboration within a framework of guided inquiry. The core elements of that guided inquiry are conceptual and representational tools that envision learning as the coordination of the activation of multiple regions of the brain. In other words, students learn because they are able to represent their ideas using MRS, as opposed to just one representational system, as is typical in traditional instructional modes. So in addition to the core curricular content, it is the pedagogy employed by an instructor that is essential to the content being successful for teaching and learning. A summary listing of particular practices are offered below.

1. Classroom collaboration. Instructors should plan for generous amounts of active collaboration in randomized groups, so that metacognitive control is influenced by the opportunity to practice critical listening and dialectical thinking on multiple perspectives.

2. Representational tools. In order for deep learning to happen, students must represent their ideas in MRS. The use of MRS promotes model-model interactions; and therefore, in accordance with TRU, a great deal of understanding. Representational systems encode for concepts, and concepts are elemental to beliefs. Coordinating concepts leads to conceptual change, and therefore belief change. The nature of conceptual change is thus related to belief development, or epistemological change.

3. Socratic dialog. The primary mode of instruction should be Socratic in nature. Concept construction is an active process requiring the kind of cognitive effort that cannot be generated by mere lecture. Conceptual frameworks are built by modeling rather than listening because questions are a resource for challenging beliefs. The key to mental development is the ability to challenge one's own understanding—which requires a change in the conceptual framework of models.

4. Journaling. Metacognitive control is the single best pathway to achievement, as well as a process for encoding knowledge that is rich with opportunity for constructing conceptual frameworks. Journaling is an excellent means by which to obtain such artifacts.

If curriculum and pedagogy are designed using the CMTCF, then both the theory and the practice that define the Teaching Enterprise will be coordinated in a manner that will inevitably lead to higher achievement for students. Knowledge and beliefs are built on concepts, but can only be justified by sound thinking and reasoning. The structure of both thinking and reasoning in terms of the TRU Learning Theory and the CMTCF provide a clear map of the cognitive and behavioral landscape that emerges in the ideal instructional setting. To this end, the primary benefactors of the TRU Learning Theory are teachers and students. Students are likely to benefit the most because it is their conceptual frameworks that are likely to change the most. However, one would expect that teachers would benefit in a similar way as they begin to reform their own conceptual frameworks in the process of developing better curriculum and assessments. Researchers in the learning sciences will also benefit from a comprehensive theory that is context-independent.

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Appendix A

Site Authorization Form

Central Arizona College

Thursday, May 7, 2015

Office of Academic Research
Grand Canyon University
College of Doctoral Studies
3300 W. Camelback Road
Phoenix, AZ 85017
Phone: 602-639-7804

Dear IRB Members,

After reviewing the proposed study, "A Grounded Theory Investigation of Thinking and Reasoning with Multiple Representational Systems for Epistemological Change in an Introductory Physics Classroom", presented by *Clark Vangilder*, I have granted authorization for Clark Vangilder to conduct research at *Central Arizona College.* I understand the purpose of the study is to determine the degree to which thinking and reasoning in terms of multiple representational systems influences epistemological change in an introductory physics classroom. Clark Vangilder will conduct the following research activities: collect archived data consisting of student journals, poll results, and interviews. It is understood that data collection is for the fall 2014 semester only, from August 18, 2014 until December 11, 2014, and that the project will end no later than December 31, 2015.

I grant permission for Clark Vangilder to *sample archived data from PHY111: College Physics 1 and PHY121: University Physics 1* at *Central Arizona College*.

I have indicated to Clark Vangilder that the school will assume the responsibilities for allowing the following research activities: *collect archived data consisting of student journals, poll results, and interviews*, and *that no student identifiers are permitted within the sample data. I will certify the anonymity of the sampled data prior to releasing it to Clark Vangilder for analysis.*

If the IRB has any concerns about the permission being granted by this letter, please contact me at the phone number listed above.

Sincerely,

William Brown
Director, Office of Institutional Planning and Research
Chairman, Institutional Review Board

William F. Brown
Printed Name

William F Brown
Signature Date

Central Arizona College
8470 North Overfield Road • Coolidge, Arizona 85128
T 520.494.5444 F 520.494.5008 www.centralaz.edu

Appendix B

Student Consent Form

Study Consent Form: Classroom Content and Coursework Data Release
A Grounded Theory Investigation of Thinking and Reasoning with Multiple Representational Systems for Epistemological Change in Introductory Physics

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STATEMENT OF CONSENT: I have read the above information, and have received answers to any questions I asked. I consent to take part in the study by releasing my archived data for analysis in research, and the transcription of recorded group interviews to which I was party.

Your Signature   Date

Your Name (printed) ______________________________

Student ID number ______________________________

Your desired Avatar ______________________________

INVESTIGATOR'S STATEMENT: "I certify that I have explained to the above individual the nature and purpose, the potential benefits and possible risks associated with participation in this research study, have answered any questions that have been raised, and have witnessed the above signature. These elements of Informed Consent conform to the assurance given by Institutional Review Board of Central Arizona College to the to protect the rights of human subjects. I have provided (offered) the subject/participant a copy of this signed consent document."

Investigator's Signature __________________________

Printed Name of Investigator __________________________

Date __________________________

Appendix C

GCU D-50 IRB Approval to Conduct Research

DocuSign Envelope ID: 5CE05E22-4F12-4055-A4A9-F6F5834D94C2

GRAND CANYON UNIVERSITY

GCU D-50 IRB Approval to Conduct Research

(IRB initiates form)

Instructions: This form must be signed prior to initiating data collection.

Learner Information

Learner Last Name: Vangilder

Learner First Name: Clark

GCU E-mail: cvangilder01@my.gcu.edu

Title of Dissertation Proposal: A Grounded Theory Investigation of Thinking and Reasoning with Multiple Representational Syste

IRB Approval to Conduct Research

Protocol #: 771284-1

Office of Academic Research: Dr. Cynthia Bainbridge

Signature: DocuSigned by: Dr. Cynthia Bainbridge

Date: July 6, 2015

Grand Canyon University - College of Doctoral Studies

Appendix D

Psycho-Epistemological Profile (PEP)

Psycho-Epistemological Profile (PEP)
Experimental Form VI

DIRECTIONS

For each of the following statements, you are to indicate your personal agreement or disagreement on the scale provided on the answer sheet. 'CD' means complete disagreement with the statement, 'MD' means moderate disagreement, 'N' means neutral, 'MA' means moderately agreement, and 'CA' means complete agreement.

Here is a sample question:
The Roman Empire fell because of moral degeneration of its rulers.

CD MD N (MA) CA

In this example, the person agrees with the statement, but not entirely, so they circled 'MA' – moderate agreement.

Your personal preference alone is required. There are no right or wrong responses. It is necessary, however, that you answer all of the questions. Be sure to clearly mark the appropriate space for each question. Use a pencil and erase any extra marks. Trust your first impression. There is no preset time limit; however, it should take approximately 30 minutes to complete the survey.

IMPORTANT! If you feel a need to qualify your scale selection, go ahead and write a brief note in the space provided for that response.

CD = Complete disagreement | MD= moderate disagreement | N = Neutral | MA = moderate agreement | CA = complete agreement

1. A good teacher is primarily one who has a sparkling entertaining delivery.

   CD MD N MA CA

2. The thing most responsible for a child's fear of the dark is thinking of all sorts of things that could be "out there".

   CD MD N MA CA

3. Most people, who read a lot, know a lot because they come to know of the nature of the world around them.

   CD MD N MA CA

4. Higher education should place greater emphasis on fine arts and literature.

   CD MD N MA CA

5. I would like to be a philosopher.

   CD MD N MA CA

6. A subject that I would like to study is biology.

   CD MD N MA CA

7. In choosing a job, I would look for one that offered opportunity for experimentation and observation.

   CD MD N MA CA

8. The Bible is still a best seller today because it provides meaningful accounts of several important areas in religious history.

   CD MD N MA CA

9. Our understanding of the meaning of life has been furthered most by art and literature.

   CD MD N MA CA

10. More people are church today than ever before because they want to see and hear for themselves what ministers have to say.

   CD MD N MA CA

CD = Complete disagreement | MD= moderate disagreement | N = Neutral | MA = moderate agreement | CA = complete agreement

80. I would be very disturbed if accused of being illogical in my beliefs.

CD MD N MA CA

81. Most great scientific discoveries come about by thinking about a phenomenon in a new way.

CD MD N MA CA

82. I feel most at home in a culture in which the expression of creative talent is encouraged.

CD MD N MA CA

83. In choosing a job, I would look for one that offered a specific intellectual challenge.

CD MD N MA CA

84. When visiting a new area, I first plan a course of action to guide my visit.

CD MD N MA CA

85. A good teacher is primarily one who is able to discover what works in class and is able to use it.

CD MD N MA CA

86. Most great scientific discoveries come about by careful observations of the phenomenon in question.

CD MD N MA CA

87. Most people, who read a lot, know a lot because they acquire an intellectual proficiency through the sifting of ideas.

CD MD N MA CA

88. I would like to visit a botanical garden or zoo.

CD MD N MA CA

89. When reading a historical novel, I am most interested in the subtleties of the personalities described.

CD MD N MA CA

90. When playing bridge or similar games, I play the game by following spontaneous cues.

CD MD N MA CA

Appendix E

What is Physics? What is Reality? Is Physics Reality?

Physics & Reality?

---

1. **What is *PHYSICS*?**

2. **What is REALITY?**

3. **Is Physics *REALITY*? Explain.**

4. **What is *UNDERSTANDING*? In other words, how do you know when you've *understood* something?**

Physics & Reality?

In a group, come to an agreement (consensus) about the four questions that you just answered. Record your findings in the space below.

Physics & Reality?

Use a computer to look up the definitions of the KEY words in the four questions. In the space below, discuss how that changes your conception of the original questions, and either your answer of the groups answer.

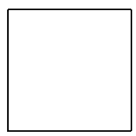
Come up with three new questions that fit the same pattern as the original questions #2 - 4. And be serious about the choices you make. ✎

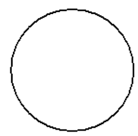
Appendix F

Numbers Do Not Add

Come Let Us Reason Together … about Numbers that DO NOT add!?!?

Today, we will show one example of how numbers do not add. You're probably wondering if the Professor has forgotten to take his meds, but I assure you, we'll find out that numbers don't add. Consider the square and the circle given below. The side of the square and the diameter of the circle are the same length.





1. Use line segments to divide each shape into four equal parts.
2. Shade one of the four equal parts in each segment.
3. Directly beneath each shape, write the appropriate numeric label for the shaded region.
4. Place an addition symbol between each shape, as well as between the numeric symbols.
5. What is your solution to each relationship?
6. Are your answers the same? How so?
7. Why don't numbers add?
8. Prepare a white board and be ready to present your findings to the class.

Appendix G

The Law of the Circle

Come Let Us Reason Together … about Making LAWS – part 2: Related IDENTITIES

A circle has at least a few measurable quantities. Circumference and diameter are just two of them—and the ones we'll pay close attention to today. Here we go…

1. Given that a LAW is a statement describing an invariable regularity, craft a LAW (in natural language) for the relationship between Circumference and Diameter in a circle.
2. In symbolic language (algebraic), write an IDENTITY for each measure stated in your LAW.
3. Turn your IDENTITY for diameter into a Fancy Form of One (*ffoo*).
4. Multiply the right-hand-side of your IDENTITY for circumference by this *ffoo*.
5. Move the denominator of your *ffoo* to be in quotient relationship with the other factor.

This new quotient is the focus of our first physical lab. We are going to measure the circumference and diameter of some objects and plot that quotient relationship on a Cartesian coordinate system.

6. Use the digital calipers to measure the diameter of the objects given to you. Record that data in a table in your daily (duplicate page) journal.
7. Use the tape measure to measure the circumference of the circles constraining the diameters in step six. Record that data in a table in your daily (duplicate page) journal.
8. Graph these coordinate pairs and find the slope of that line.
9. How would you change your result from step five?
10. Do you now have a Law, an Axiom, an Equation, or all of the above? Explain. Feel free to use a dictionary to help select a term.
11. Prepare a white board and explain yourself when called upon to do so.

Appendix H

The Zeroth Laws of Motion

Concerning Laws of Motion

For this activity, record **ALL** of your work in the duplicate page journal.

The purpose of this activity is for you to apply the conceptual and representational tools learned and used in previous lab activities in order to develop an understanding of motion.

Describing Motion Naturally

1. In your group, craft a natural language statement describing the simplest motion of the simplest object that you can imagine.
2. Draw a picture or diagram that is consistent with the statement from above.
3. List the changes related to the motion of your object.
4. What changes are "the same" throughout the motion of your object?
5. What changes are "**not** the same" throughout the motion of your object?
6. Are any of the changes related? Explain.
7. Is there anything about motion that is undeniably true no matter what motion you are trying to describe? Explain.
8. Write a natural language statement of law (empirically familiar regularity) that sums up your observations.

★★★ Check with the instructor before moving to the next step ★★★

Describing Motion Mathematically

9. Write mathematical identity statements for your change quantities.
10. Create a fancy-form-of-one (***ffoo***) for the change quantity that is independent from the other(s). Explain why it is independent.
11. Use the ***ffoo*** on the change quantity that is dependent on the other(s).
12. Adjust your mathematical axiom so that the change quantities are *connected* to one another by virtue of the way that you've encoded them in a quotient relationship.
13. Simplify your axiom as best you can. Feel free to rename/re-label any factor. Explain.

★★★ Check with the instructor before moving to the next step ★★★

---

14. Prepare a whiteboard and be ready to defend your findings in the larger group.

Concerning Certain Laws of Motion … again ☺

For this activity, record **ALL** of your work in the duplicate page journal.

The purpose of this activity is for you to apply the conceptual and representational tools learned and used in previous lab activities in order to develop an understanding of motion.

Describing Changes in Motion Naturally

1. In your group, consider the First Zeroth Law that you found in the last lab activity. Is there any aspect of motion—besides a change in position—that must also occur in non-zero time? Explain.

2. Draw a picture or diagram that is consistent with that statement from above.

3. Write a natural language statement of law (empirically familiar regularity) that sums up your observations.

★★★ Check with the instructor before moving to the next step ★★★

Describing Changes in Motion Mathematically

4. Write mathematical identity statements for your change quantities.

5. Create a fancy-form-of-one (***ffoo***) for the change quantity that is independent from the other(s).

6. Use the ***ffoo*** on the change quantity that is dependent on the other(s).

7. Adjust your mathematical axiom so that the change quantities are connected to one another by virtue of the way that you've encoded them in a quotient relationship.

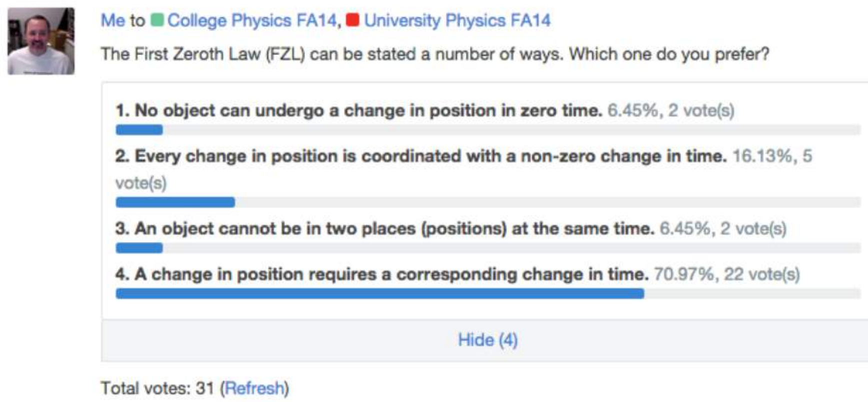
8. Simplify your axiom as best you can. Feel free to rename/re-label any factor. Explain.

★★★ Check with the instructor before moving to the next step ★★★

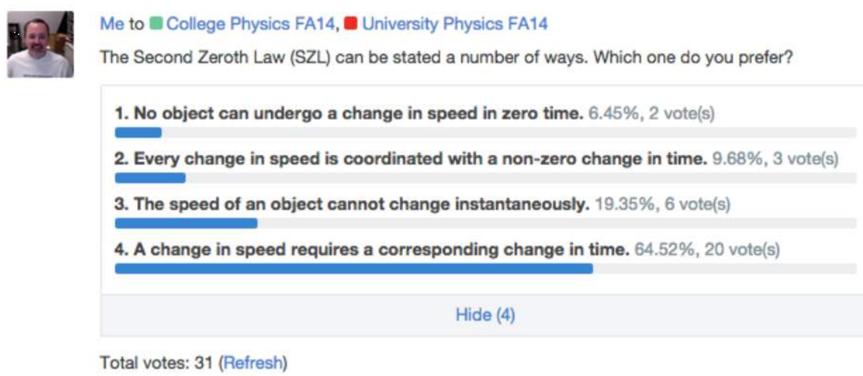
9. Prepare a whiteboard and be ready to defend your findings in the larger group.

FZL & SZL Polls Journal

So we have these poll results: the first one concerning the First Zeroth Law (FZL)…



…and the second one concerning the Second Zeroth Law (SZL).



In this journal entry, (1) provide a rank ordering of each law, with (2) a justification for why you ranked them the way that you did. Also, (3) in general terms, attempt to describe what is different about each version of both laws. Address the following questions as well.

1. How has your **thinking** changed as a result of these activities? Explain.
2. How has your **reasoning** changed as a result of these activities? Explain.
3. How has your **understanding** changed as a result of these activities? Explain.
4. Have any **personal beliefs** changed as a result of these activities? Explain.
5. Has the **way that you come to believe** changed as a result of these activities? Explain.

Appendix I

End of Term Interview

Fall 2014 PHYSICS End-of-term Interview Questions

1. **How has your thinking changed as a result of this experience?**

2. **How has your reasoning changed as a result of this experience?**

3. **How has your understanding changed as a result of this experience?**

4. **Do any of these changes impact your thinking and reasoning outside of this experience? How so?**

5. **Do any of the changes in your understanding impact your beliefs about anything? How so?**

6. **In what ways have any personal beliefs changed as a result of this experience?**

7. **How would you describe conceptual change, and have you experienced any during this experience?**

8. **What conceptual changes have you identified in yourself?**