THE DEVELOPMENT OF VETERAN 9TH-GRADE PHYSICS TEACHERS' KNOWLEDGE FOR USING REPRESENTATIONS TO TEACH THE TOPICS OF ENERGY TRANSFORMATION AND TRANSFER

A Dissertation

Presented to

The Faculty of the Graduate School

At the University of Missouri

In Partial Fulfillment

Of the Requirements for the Degree

Doctor of Philosophy

By

ANDREW WEST

Dr. Mark Volkmann, Dissertation Supervisor

APRIL 2011

The undersigned, appointed by the dean of the Graduate School,

have examined the dissertation entitled

THE DEVELOPMENT OF VETERAN 9TH-GRADE PHYSICS TEACHERS' KNOWLEDGE FOR USING REPRESENTATIONS TO TEACH THE TOPICS OF ENERGY TRANSFORMATION AND TRANSFER

Presented by Andrew West

A candidate for the degree of

Doctor of Philosophy

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

____

Professor Mark J. Volkmann, Dissertation Supervisor

____

Professor Patricia M. Friedrichsen

____

Professor Thu Suong Thi Nguyen

____

Professor Hannah Alexander

Dedicated to my dad, Bill West, who would have loved this entire process, to Sandi Abell, whose legacy is reflected in these pages, and to my wife, Sara, the love of my life.

ACKNOWLEDGEMENTS

This dissertation is the end product of five years of graduate studies. As such, the fingerprints of many individuals are present throughout its pages. I would be remiss not to acknowledge these folks.

Mark Volkmann, your mentorship over the past five years – academically, professionally, and personally – has been a huge gift. I have grown as a scholar, as an educator, and as a man because of your guidance. You have a gift for asking excellent questions that challenge my thinking and push me forward. Your genuine interest in both my professional and personal life will not be forgotten.

Pat Friedrichsen, Thu Suong Nguyen, and Hannah Alexander. Thank you so much for your willingness to sit on my committee and to give so willingly of your time. I know that it is a huge commitment, and I have learned much from each of you. Thank you for sharing your expertise, both in the classroom and as members of my committee. I look forward to continuing to work with you in the future.

Lloyd Barrow, Debi Hanuscin, Marcelle Siegel, and Anna Waldron. Thank you all for your expertise and support, both in and out of the classroom. You are an amazingly talented and gifted group of educators, and you have forever changed the way I think about science teaching and learning.

Aaron Sickel, you've become a dear colleague and friend. Thank you so much for sharing your life with me (and my family), for asking good questions, and for being excellent at what you do. I have learned much from you. I'm looking forward to "Uncle Aaron" being part of the West family for many years to come.

Steve Witzig, thanks for your friendship. You and Aaron have been the best roomies a guy could ask for. Thanks for bringing great energy and enthusiasm to all that you do and for pushing my thinking.

John Lannin, Kathryn Chval, Fran Arbaugh, and the rest of the Re-SMAR^{2}T team, thank you for your insight into PCK, for helping me think deeply about PCK, for your ideas on analysis of PCK, and for your generous support of this study.

Meera Chandrasekhar, Sara Torres, Sarah Hill, and the rest of the Physics First project staff, thank you for your willingness to have me as part of the team. I have learned much from each of you and this study would not have been possible without my involvement in the project.

To my three participants, thank you for opening up your classrooms to me. I know that it was added work and time on your end, and I appreciate it. Also, thank you for your willingness to spend significant time talking with me about your instruction. Without your participation, this study would be impossible.

To my West and Powell family, thank you so much for you constant support and interest in my studies. You encourage me more than you know. I look forward to journeying through the next chapter of my life with all of you.

Chonchi, you are the most important person in the world to me. You are a constant source of encouragement, support, and unconditional love. You have made me a better man, and without you, I would not be where I am. I look forward to our many, many, many years together.

And finally, to my Lord and Savior Jesus Christ, through whom and for whom all things were created, and without whom, this endeavor is simply chasing after the wind.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The purpose of this study was to explore and identify the experiences that informed the development of three veteran (15+ years of teaching experience) 9^{th} grade physics teachers' specialized knowledge, or PCK, for using representations to teach the topics of energy transformation and transfer. Through the lens of phenomenography, the study was guided by the assumption that there are a limited number of experiences in which teachers engage throughout their career that contribute in significant ways to the development of their knowledge. The primary sources of data were observations of an entire unit of instruction on energy and a series of four stimulated-recall interviews throughout the unit of instruction. The stimulated recall interviews focused on the participants' instruction and knowledge regarding the representations used throughout the energy unit. These data sources were supported by interviews focused on the participants' work history and professional development as well interviews focused on their unit/lesson plans. The results of the phenomenographic analysis revealed that nine categories of experiences informed the development of the three participant's PCK for using representations to teach the energy topics. The categories included: 1) teaching experience, 2) Physics First professional development, 3) other school district-supported professional development 4) collaboration with current colleagues, 5) past collaboration with experienced teachers, 6) academic experiences as a learner of science, 7) school district expectations, 8) collaboration with university faculty and other university professional development, and 9) non-academic life experiences. The analysis also revealed that as a result of engaging in the nine experiences, the participants developed more integrated knowledge for using representations in their instruction, which included

understandings regarding the essential features of specific representations, knowledge of barriers to student learning regarding representations, and knowledge of how to help students develop understandings about specific representations. The results of the study highlight that the development of PCK for using representations to teach topics in energy is best supported through a combination of reflection on teaching experience, collaboration with colleagues, and professional development that provides topic-specific instruction in terms of content and pedagogy. These findings have implications for pre-service teacher preparation programs as well as in-service teacher professional development.

CHAPTER ONE: INTRODUCTION

One of the most significant differences between a master physics teacher and an expert physicist is the teacher's ability to help the novice learner develop rich understandings of the physics subject matter. Although it was once thought that knowledge of subject matter alone was sufficient for teaching novices, a growing body of research suggests otherwise. This body of research points to another type of knowledge that is argued to be "uniquely the providence of teachers" (Shulman, 1987, p. 8). This knowledge represents the transformation of subject matter knowledge into the most powerful ways of "representing and formulating the subject that make it comprehensible to others" (Shulman, 1986, p. 9). Researchers have labeled this specialized knowledge for teaching *pedagogical content knowledge*, or PCK. PCK is thought to result from the transformation of a teacher's knowledge of the subject matter (e.g., facts, concepts, etc), knowledge of the context (e.g., school, community, etc), and knowledge of general pedagogy (e.g., classroom management, learners and learning, etc) into specialized knowledge for teaching (Grossman, 1990; Magnusson, Krajcik, & Borko, 1999). Because of its interconnectedness to a variety of knowledge types, PCK is thought to develop incrementally over time in relation to the teacher's experiences. Consequently, investigations into the experiences of teachers that inform this development are of the utmost importance to researchers (Abell, 2008; van Driel, Verloop, & de Vos, 1998).

In an effort to promote the development of this specialized knowledge for teaching, pre-service teachers (students preparing to be teachers) and in-service teachers (teachers that are actively teaching) engage in a variety of teacher preparation and professional development experiences throughout their careers. These experiences often include university coursework, peer support groups, seminars, collaboration with cooperating teachers (teachers who open their classrooms for pre-service teachers), specially designed professional development programs, book clubs, mentoring, and collaboration with teaching teams and departments (Arhar & Crowe, 2002; Loucks-Horsley, Love, Stiles, Mundry, & Hewson, 2003; J. Wang & Odell, 2002). School districts and universities allocate a great deal of time, energy, and money in order to provide these experiences for teachers because of the potential impact of these experiences on the development of knowledge for teaching, and ultimately improved student learning. However, although there are extensive numbers of studies in the research literature regarding the utility of specific teacher development experiences in supporting teacher knowledge growth in specific knowledge areas (e.g., subject matter knowledge, pedagogical knowledge) (e.g., J.L. Edwards, 1993; J. L. Edwards, Green, Lyons, Rogers, & Swords, 1998; Ingersoll & Kralik, 2004; Loucks-Horsley et al., 2003; van Driel, 1999), the literature is limited in terms of studies that investigate the connection between specific teacher experiences and their influence on the development of PCK. Studies that investigate the PCK of veteran (experienced) teachers and the development of this knowledge are even more limited (Abell, 2008).

Therefore, the purpose of this study is to contribute to the research literature regarding the development of PCK in veteran physics teachers. Specifically, this study is focused on describing and understanding the experiences of veteran high school physics teachers – particularly, the experiences that have informed and promoted the development of PCK.

Statement of the Problem

The need for a study investigating the experiences that have informed the development of PCK of veteran high school physics teachers emerges from the work of scholars in three areas: 1) representations in physics, 2) teacher knowledge, and 3) development of teacher knowledge. In the following section, I will describe the work of scholars in these three areas and conclude by highlighting a central problem that emerges from this work. In addition, I include a description of the experiences in my life that brought me to this problem.

Representations in Physics

It has been suggested that in physics, there are no purely abstract understandings of physical concepts (Meltzer, 2005). Instead, physical concepts are always understood and communicated using some form of representation. These representations can be concrete, verbal, symbolic, visual, or gestural in nature (Gilbert, 2007) and include pictures, graphs, diagrams, equations, tables, analogies, models, and verbal descriptions. These representations, however, are incomplete by themselves as tools for understanding and communicating ideas in physics (Brookes & Etkina, 2007). Instead, the usefulness of a representation as a tool for understanding and communicating ideas depends upon one's capacity to navigate the rich information contained within the representation as well as the ability to assimilate, coordinate, and move between many different representations. In fact, fluency and expertise in physics is characterized by an individual's ability to represent concepts in a number of ways and to move back and forth between them (Gardner, 1991; Gilbert, 2007; Van Heuvelen & Zou, 2001). It is therefore an important goal in high school physics education that students develop similar capacities and understandings, including the ability to extract the rich information contained within various representations, the prowess to manipulate concepts using a variety of representations, and the competence to move back and forth between multiple representations (Beichner, 1994; Meltzer, 2005). However, numerous studies have highlighted the difficulties that students bring to the task of understanding representations in these ways (Albe, Venturini, & Lascours, 2001; Beichner, 1994). Consequently, it is up to the classroom teacher to help students overcome these difficulties.

My Journey

My journey towards helping students develop conceptually rich understandings of physics using representations began in high school – specifically, in my junior-year physics course. I remember watching my physics teacher stand at the chalkboard while he lectured on concepts of work and energy and force. I remember that I enjoyed his stories, his demonstrations, and "lab day," but loathed taking notes and completing worksheets. Surprisingly (or maybe not surprisingly), I remember the specifics of very few assignments, save one. The assignment was to select one topic that we had covered during the course and teach a portion of it to an elementary class of our choosing. We were given access to any resources and supplies that would aid us in our task of making the topic accessible to elementary students. I chose the topic of electromagnetism because I thought that second grade students would enjoy wrapping copper wire around a nail, attaching a battery to it, and seeing how many paperclips they could pick up. As it turns out, they did. I walked away feeling like a million bucks because the activity was successful and the students loved me.

In college, my first conceptual physics course at Montana State University was taught by Dr. Gregg Francis, a professor of physics education and collaborator with the Physics Education Group based at the University of Washington. I was captivated by Gregg's charisma, his sense of humor, his PowerPoint presentations, and his demonstrations. For me, I felt that Dr. Francis possessed all the pieces of an effective physics teacher. He had the stories and demonstrations that I enjoyed so much as a high school student, but he added a layer with his dynamic use of animated PowerPoint presentations and his charismatic personality. Consequently, these were the characteristics I tried to emulate as a first-year high school physics teacher.

I stepped into the high school classroom on my first day of teaching and assumed that I had all the characteristics of an effective physics teacher. I had my content knowledge, my stories, my demonstrations, some fun activities, and my animated PowerPoint slides. And like my first experience teaching electromagnetism to second graders, I knew that I was going to be successful because my students were going to love me – and then reality happened. Two weeks into teaching, the students were bored with my slideshows, I had run out of demonstrations and stories, and the activities that I had planned turned out to not be as fun as I thought they would be. All I had left was my content knowledge, and as I tried to shove this knowledge down my students' throats, I lost what charisma I had left. The remainder of that first year was miserable, but it sent me on a mission to discover how to do this thing called "teaching physics" better. Two more years in the high school classroom and five years of graduate school have taught me something that I'm sure Dr. Francis and the Physics Education Group were well aware of – it takes more than content knowledge, fun activities, and animated PowerPoint slides to help students build conceptually rich understandings of the various ways in which concepts are represented in physics.

Teacher Knowledge

Over twenty years ago, Lee Shulman (1986) posed a question that I wish I would have wrestled with prior to ever taking a step into the classroom: "How does the successful college student transform his or her expertise in the subject matter into a form that high school students can comprehend?" (p. 8). This was my problem. After graduating from college, I had what I thought to be sufficient knowledge of the physics content and equated this to having all the knowledge that I would need for teaching high school physics. I had observed and participated in lectures, labs, activities, and demonstrations and rationalized that I would simply do all of these things with my students in the same (albeit simplified) ways that my instructors did with me. I never considered that if I wanted my students to really comprehend the subject matter, I would need knowledge of physics that extended beyond the content and the strategies that I had observed. It never occurred to me that expert teachers might have knowledge for teaching that extended beyond their knowledge of the content or knowledge of some general teaching strategies.

In 1986, Shulman suggested that expert teachers draw upon three distinct categories of knowledge: 1) subject matter knowledge, 2) curricular knowledge, and 3) pedagogical content knowledge. Subject matter knowledge included a teachers' knowledge of what something is (substantive knowledge) and why something is the way it is (syntactic knowledge). This was knowledge that teachers were supposed to develop in their college content courses. Curricular knowledge involved knowledge of programs designed for teaching particular topics, knowledge of available instructional materials, and knowledge of when and why to use said programs and instructional materials in particular circumstances. This was knowledge that was ideally learned in teacher education courses. But it was the final category of pedagogical content knowledge, or PCK, that represented the essential category of teacher knowledge that was necessary for transforming subject matter knowledge into forms accessible to high school students (Grossman, 1990; Magnusson et al., 1999). Shulman (1986) defined PCK as "the dimension of subject matter for teaching…the most useful forms of representation of [ideas], the most powerful analogies, illustrations, examples, explanations, and demonstrations – in a word, the ways of representing and formulating the subject that make it comprehensible to others" (p. 9).

It is this knowledge that separates the expert in the subject matter or the expert in general teaching approaches from the expert physics teacher. The individual who only has an understanding of the subject matter is limited in his or her ability to share that knowledge in ways that are understandable and meaningful to others. The individual who only has knowledge of teaching approaches, but limited subject matter knowledge, knows how to plan general instruction but does not know what instruction is best for learning conceptually difficult ideas. It is the teacher who has developed PCK – the teacher whose knowledge of the subject matter and knowledge of teaching strategies have been transformed into knowledge for teaching specific topics to specific students in specific contexts for specific reasons – it is this teacher that can "plan and enact lessons that help students develop deep and integrated understandings" (Magnusson et al., 1999,

p. 95). In short, it is this person with highly developed PCK that can be characterized as an expert teacher.

PCK is consequently a useful construct for exploring the knowledge that physics teachers bring to the task of helping students overcome the difficulties of understanding physics representations in conceptually rich and meaningful ways. The construct of PCK highlights the idea that possessing knowledge of the representations used in high school physics is inadequate by itself for helping others build similar understandings in powerful ways. Instead, subject matter knowledge must be transformed into knowledge for teaching. The construct of PCK provides a framework for understanding and describing the transformation of content knowledge and general pedagogical knowledge into knowledge for teaching students in specific contexts. Because of its utility in helping researchers characterize and understand teacher knowledge, PCK research has been a fruitful line of research in science education for over twenty years (Abell, 2008).

It is important at this juncture to emphasize that PCK represents the transformation of various types of knowledge into a specialized type of knowledge for teaching that is the most powerful for teaching particular topics to particular students in particular contexts (Magnusson et al., 1999). Consequently, many types of knowledge for teaching can inform a teacher's PCK, but a teacher can also have knowledge for teaching that does not directly inform his or her PCK. Put another way, a teacher may have general knowledge for teaching (e.g., knowledge of the subject matter, knowledge of teaching strategies, knowledge of teaching philosophies, etc) that has not been transformed in specialized and powerful ways for teaching (PCK). I will discuss this point in greater detail in the theoretical framework section of this study, but the distinction is critical in the following section – general knowledge for teaching is often related to, but qualitatively different than PCK.

Development of Teacher Knowledge

As is the case with other types of knowledge, PCK is generally understood to be a dynamic type of knowledge that an individual develops – in other words, the transformation of other types of general knowledge for teaching into PCK is a process that happens incrementally over time through the experiences of the individual (Friedrichsen et al., 2007, April; van Driel et al., 1998; C. Y. Wang & Volkmann, 2007, April). However, the processes and experiences that contribute in meaningful ways to the development of PCK are less clear.

In general, it is thought that the development of general knowledge for teaching is informed by a variety of sources. Borrowing from Lortie (1975), Grossman (1990) suggests that a key player in the development of knowledge for teaching (per the distinction above, not necessarily PCK) is the "apprenticeship of observation" (p. 10), referring to the cumulative experiences of the individual as a student. From this perspective, teacher's ideas of how to teach particular topics are based on their memories of how they were taught. Evidence of this apprenticeship of observation is demonstrated by the ways in which teachers in different countries plan and sequence lessons. Research by Stigler and Hiebert (1999) indicates that teachers follow culturally-specific "scripts" when planning and sequencing lessons. These scripts are unique to each country, supporting the notion that teachers oftentimes teach how they were taught. However, the ways in which teachers plan and sequence lessons are often inconsistent with current views regarding the ways in which people learn (Donovan & Bransford, 2005; National

Research Council, 2000) and approaches to teaching science touted by research-based national reform documents (American Association for the Advancement of Science, 1993; National Research Council, 1996). Consequently, teaching that is informed only by the apprenticeship of observation contains elements of a general knowledge for teaching but seldom reflects sophisticated PCK. Because knowledge for teaching does not develop exclusively through ones' experiences as a student, pre-service and in-service teachers engage in a wide range of experiences intended to promote the development of knowledge for teaching.

The first experiences focused on developing knowledge for teaching in which most beginning teachers engage are usually subject-specific methods courses (Grossman, 1990). These courses typically occur at colleges and universities and they focus on helping students develop the knowledge that they need for teaching, including understanding the nature of the discipline, rationales for teaching specific topics, the educational psychology of learners, curriculum, current trends and innovations for teaching the subject, and specific teaching techniques (Houston, 1983). Students typically take their methods courses along with their science content courses. Combined, the methods courses and the content courses are a central component of teacher training programs and they are intended to provide students with a solid knowledge base to begin teaching.

However, it has been suggested that the primary source that informs the development of knowledge for teaching is actual teaching experience (Shulman, 1987; van Driel et al., 1998). Once in the classroom, the knowledge that the teacher gained in his or her content and methods courses must be revisited as the teacher navigates the complexities of the interpersonal, academic, pedagogical, and nurturing aspects of teaching (Brookhart & Freeman, 1992), including issues of classroom management and student motivation (J. Wang & Odell, 2002). Beginning teachers must also negotiate the conceptions of teaching and learning that they gleaned from their methods courses in relation to their own experiences as learners (Adams & Krockover, 1997), including discrepancies between how they think that teaching should occur versus the alternatives touted in their courses (Beach & Pearson, 1998). And they must do all of this while building and maintaining relationships with students, colleagues, administrators, and community members. Consequently, once in the classroom, beginning teachers often engage in a wide range of additional support structures and experiences designed to facilitate the development of knowledge for teaching.

For instance, during the beginning years of teaching, most teachers are provided with mentors. Generally the mentor is a more experienced and more knowledgeable individual that provides guidance, advice, support, and/or feedback to the beginning teacher (Smith & Ingersoll, 2004). The primary purpose of the mentor is to support the beginning teacher in developing knowledge that will improve his or her teaching. However, this support may or may not be explicitly aimed at promoting the development of PCK (Jonson, 2002; Zubrowski, Troen, & Pasquale, 2007).

A second example of an experience designed to promote the development of knowledge for teaching is the professional learning community, or PLC (DuFour, 2004). In general, a PLC is composed of a group of teachers intent on improving teaching and learning. The emphasis is on working collaboratively to develop knowledge as a group, and as individuals, that will improve classroom instruction. The members of the PLC hold each other accountable for results and the issues upon which the group focuses are determined by the group itself. Because of this, the knowledge for teaching gleaned by the individual from the PLC may or may not represent PCK.

A third example of an experience intended to promote the development of knowledge for teaching is lesson study (Lewis, 2002; Loucks-Horsley et al., 2003; Stigler & Hiebert, 1999). Lesson study may be defined as “teachers collaborating on the development and refinement of lessons” (Loucks-Horsley et al., 2003, p. 185). Lewis (2002) describes lesson study as “a complex process, supported by collaborative goal setting, careful data collection on student learning, and protocols that enable productive discussion of difficult issues” (p. 1). Lesson study is practice-based learning, where teachers have the opportunity to grapple with authentic instructional issues encountered in classrooms and schools. Lesson study is a collaborative process that connects what teachers already know to new ideas, relevant to their teaching. In the lesson study, teachers set goals, plan lessons, teaching and observe the lesson, discuss and revise the lesson, and reflect on the lesson, all with the goal of improving instruction and building knowledge.

Mentoring, PLCs, and lesson study represent a small slice of the experiences in which a teacher might engage beyond coursework that are intended to help the teacher develop knowledge for teaching. Other experiences might include case discussions (where teachers examine videos or narrative stories of teaching and learning in order to stimulate discussion and reflection), immersion experiences (where teachers are given opportunity to fully engage in inquiry activities as learners), seminars, book clubs, or summer professional development programs (Arhar & Crowe, 2002; Loucks-Horsley et al., 2003; J. Wang & Odell, 2002). In all of these cases, however, the influence of the experience on the development of general knowledge for teaching versus the influence of the experience on the development of PCK is unclear.

The Problem

In this section, I have highlighted the work of scholars in the areas of physics representations, teacher knowledge, and the development of teacher knowledge. Taken together, these three areas begin to paint a picture regarding the expectations of high school physics teachers and the knowledge required to meet these expectations. Specifically, it is clear that understanding in high school physics hinges on students developing conceptually rich understandings of the various representations used to communicate ideas. It is also clear that developing these abilities is difficult for students. Consequently, it is the teacher's responsibility to teach in such a way that students can overcome these difficulties. The teacher's ability to teach in this manner requires more than knowledge of the physics content or general knowledge for teaching. It requires specialized knowledge for teaching, or PCK, that includes knowledge of using representations to teach specific concepts to specific students in specific contexts and determining which representations are most powerful for particular contexts. But it is also clear that not all teachers have this PCK. Instead, PCK develops over time through the transformation of other types of knowledge. This development and transformation of knowledge is informed by the teacher's various experiences. However, not all experiences serve to inform the development of PCK. Consequently, it is the nature of the experiences that inform the development of PCK that serve as the focus of this study. Specifically, I am interested in understanding and describing the experiences of veteran high school physics teachers that inform and promote the development of specialized knowledge for using representations to teach specific topics to high school students.

Theoretical Framework

This investigation into the experiences of veteran high school physics teachers that inform and promote the development of specialized knowledge for using representations to teach specific topics to high school students is informed by three areas of theory and research: 1) PCK, 2) teacher learning, and 3) representations in science. These three areas are rich with assumptions informed by theory and empirical research. In the following section, I will provide an overview of the assumptions that dominate each area and conclude with the specific assumptions that I have adopted for this study.

Pedagogical Content Knowledge

Up to this point, I have described PCK as the transformation of various types of knowledge into a specialized type of knowledge for teaching that is the most powerful for teaching specific topics to specific students in specific contexts. I have also claimed that PCK is uniquely the providence of teachers and that teachers develop this knowledge over time. In this section, I will expand my conception of PCK to include PCK as a construct consisting of five interconnected components and I will distinguish PCK from a teacher's general knowledge for teaching. My conception of PCK is informed by the work of several researchers.

PCK entered the educational research scene through the work of Lee Shulman and his colleagues at Stanford University in the mid-1980s. In his now landmark presidential address at the 1986 AERA Annual Meeting, Shulman (1986) challenged the thinking of the day that possessing knowledge of a subject matter equated to the ability to teach the subject to others. Shulman distinguished content (what is known) from pedagogy (how to teach it) and criticized the fact that researchers had not investigated "how subject matter was transformed from the knowledge of the teacher into the content of instruction" (p. 6) to address questions such as "where do teacher explanations come from," and "how do teachers decide what to teach, how to represent it, how to question students about it and how to deal with problems of misunderstanding?" (p. 8). Shulman postulated that there were three types of knowledge that grow in the minds of teachers: 1) subject matter content knowledge, 2) curricular knowledge, and 3) pedagogical content knowledge.

As previously discussed, subject matter content knowledge included a teachers' knowledge of what something is and why something is the way it is while curricular knowledge involved knowledge of programs designed for teaching specific topics, knowledge of available instructional materials, and knowledge of when and why to use said programs and instructional materials in specific circumstances. The linchpin, however, was PCK, which represented "the dimension of subject matter for teaching" (p. 9) that included the most useful forms of representations, analogies, illustrations, examples, explanations, and demonstrations – "in a word, the ways of representing and formulating the subject that make it comprehensible to others" (p. 9). Shulman's work set the stage for other researchers to explore his ideas – and they did.

In 1990, Pamela Grossman published a book exploring teacher knowledge and the construct of PCK in the context of English education (Grossman, 1990). Drawing heavily from Shulman's (1986) work, she argued that the literature on teacher knowledge pointed to a view of PCK as a dynamic relationship between three types of knowledge: 1) subject matter knowledge, 2) general pedagogical knowledge, and 3) knowledge of context (Figure 1).

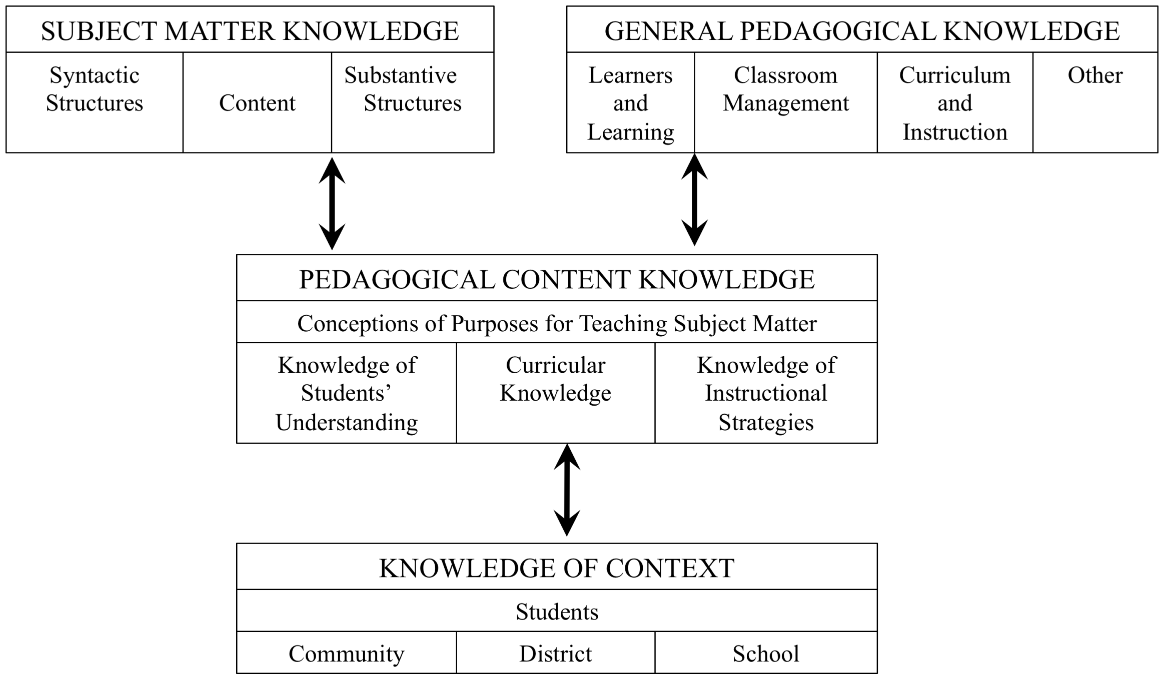

Figure 1. Model of teacher knowledge. Adapted from *The Making of a Teacher: Teacher Knowledge and Teacher Education,* by P.L. Grossman, 1990, New York: Teachers College Press.

For Grossman (1990), subject matter knowledge consisted of content knowledge (the major facts and concepts within a field and the relationship between them), knowledge of syntactic structures (the canons of evidence and proof within the discipline and how knowledge claims are evaluated), and knowledge of substantive structures (the various paradigms within a field that affect how the field is organized and the questions that guide inquiry) (p. 6). General pedagogical knowledge referred to the general knowledge, beliefs, and skills related to teaching, including "knowledge and beliefs concerning learning and learners; knowledge of general principles of instruction; knowledge and skills related to classroom management; and knowledge and beliefs about the aims and purposes of education" (p. 6). Knowledge of context included "knowledge of the districts in which teachers work; knowledge of the school setting; and knowledge of specific students and communities" (p. 9).

Grossman (1990) argued that PCK represented the transformation of these three types of knowledge into a new type of knowledge for teaching that was more powerful than its constituent parts. Additionally, Grossman suggested that PCK was comprised of four central components (pp. 8-9):

1. Knowledge and beliefs about the purposes for teaching a subject at different grade levels
2. Knowledge of students' understanding
3. Curricular knowledge
4. Knowledge of instructional strategies and representations for teaching particular topics

These four components of knowledge, viewed collectively, encompassed a teacher's PCK. In Grossman's (1990) model, the collective components of PCK were understood to relate in a reciprocal fashion with the other three types of knowledge (i.e., subject matter knowledge, general pedagogical knowledge, and knowledge of context). In this sense, the three types of knowledge informed PCK and PCK consequently informed the three types of knowledge. This relationship was represented in the model by the use of double arrows (see Figure 1).

Nearly ten years later, Magnusson, Krajcik, and Borko (1999) re-conceptualized Grossman's (1990) model in the context of science teacher knowledge and beliefs. They described PCK as "a teacher's understanding of how to help students understand specific subject matter. It includes knowledge of how particular subject matter topics, problems and issues can be organized, represented, and adapted to the diverse interests and abilities of learners, and then presented for instruction" (p. 96). Like Grossman, Magnusson et al. viewed PCK as the transformation of one's knowledge of context, subject matter, and pedagogical knowledge into specialized knowledge for teaching. However, unlike the Grossman model of PCK that included four components, Magnusson et al. suggested that PCK could be represented by five components: 1) orientations toward science teaching, 2) knowledge and beliefs about science curriculum, 3) knowledge and beliefs about students' understanding of specific science topics, 4) knowledge and beliefs about assessment in science, and 5) knowledge and beliefs about instructional strategies for teaching science (see Figure 2).

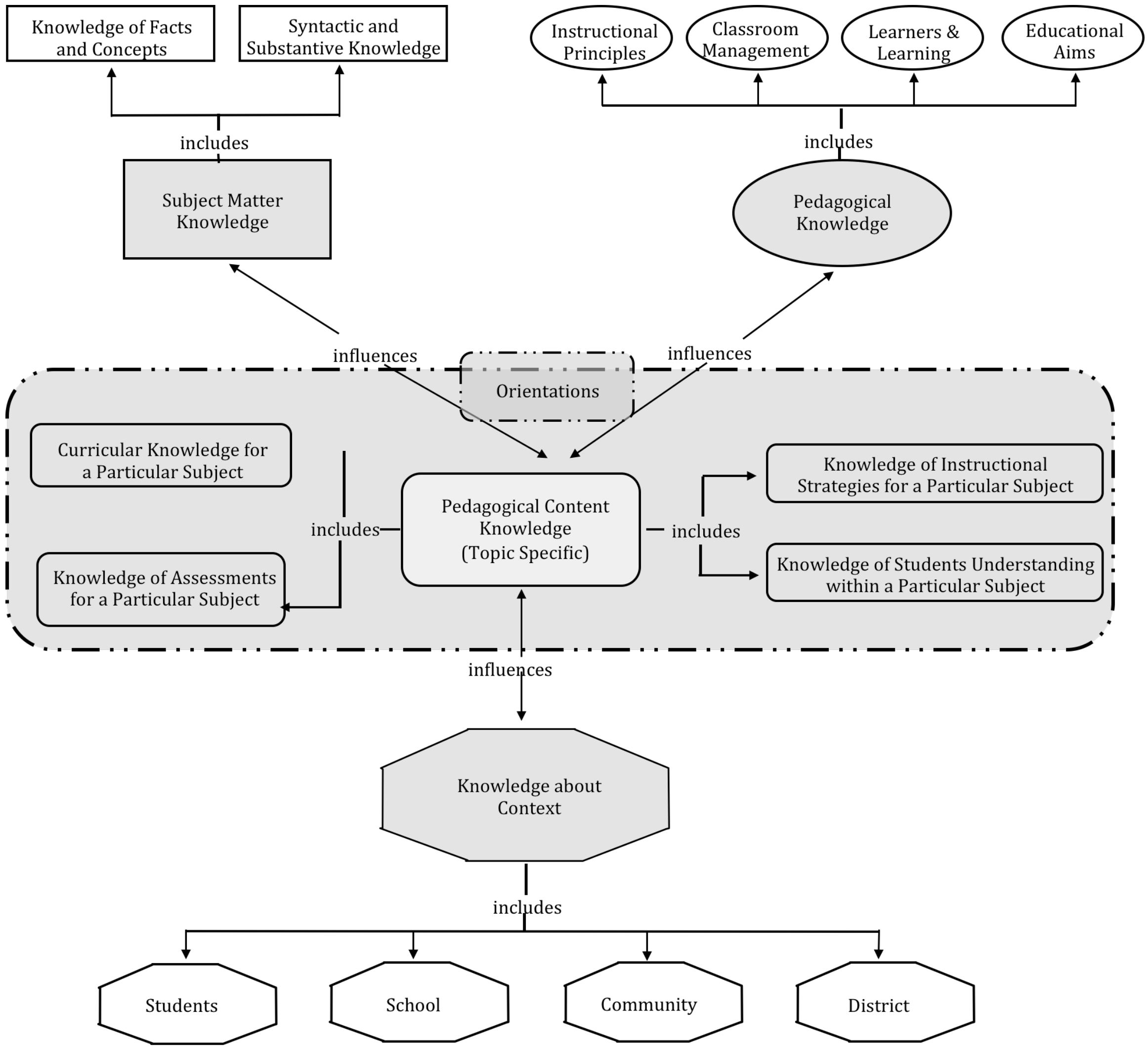

Figure 2. Transformative model of PCK from the Re-SMAR^{2}T Project at the University of Missouri-Columbia, Sandra K. Abell, PI. Adapted from "Nature, Sources, and Development of PCK for Science Teaching," by S. Magnusson, J. Krajacik, and H. Borko, 1999, p. 99. In J. Gess-Newsome and N.G. Lederman (Eds.). *Examining PCK: The Construct and its Implications for Science Education.* Boston, MA: Kluwer Academic Press.

In the Magnusson et al. (1999) model of PCK, the "orientations towards science teaching" component is thought to inform the other four components, and like the Grossman (1990) model, all of the components of PCK are thought to behave reciprocally and as inextricably connected. Magnusson et al. defined the five components of PCK for science teaching in the following ways:

- *Orientations*: Knowledge and beliefs about the purposes for teaching science at a particular grade level. An orientation represents a general way of viewing or conceptualizing science teaching (p. 97).

- *Knowledge of curriculum*: Knowledge of the mandated goals and objectives and knowledge of specific curricular programs and materials (p. 103).

- *Knowledge of student understanding*: Knowledge teachers have about students in order to help them develop specific scientific knowledge, including knowledge of the requirements for learning specific science concepts and knowledge of the areas of science that students find difficult (p. 104).

- *Knowledge of assessment*: Knowledge of the ways that might be employed to assess the specific aspects of student learning that are important to a particular unit of study (p. 109).

- *Knowledge of instructional strategies*: Knowledge of general approaches to or overall schemes for enacting science instruction (subject-specific) AND knowledge of specific strategies that are useful for helping students comprehend specific science concepts (topic specific). This component includes knowledge of representations and activities (pp. 110-111).

As described above, the five components of PCK in the Magnusson et al. (1999) model are understood as being interconnected – that is, any single component does not act in isolation or independently of the others. For this reason, I will consider PCK holistically in my study by exploring the connections between the five components. However, for the purposes of theorizing, it can be helpful to focus on a particular component of PCK. Because my study focuses on teachers' knowledge for using representations to teach a particular topic in physics, I will focus on the "knowledge of instructional strategies" component of PCK, as a teacher's knowledge of representations falls into this component in the Magnusson et al. model. Consequently, elaboration on this component is in order.

Magnusson et al. (1999) conceptualized a teacher's knowledge of instructional strategies in two categories: 1) subject-specific knowledge and 2) topic-specific knowledge. Subject-specific knowledge referred to a teacher's knowledge of general approaches to science instruction. These subject-specific strategies are thought to relate closely to a teacher's orientations to teaching science. For example, researchers have proposed various "learning cycles" around which teachers can sequence their instruction. In the 5E learning cycle (Bybee, 1997), students engage in and explore scientific ideas before any type of explanation. This approach to sequencing instruction is based on a constructivist orientation to science instruction, which views learning as a process of constructing understanding (e.g., von Glasersfeld, 1995; Vygotsky, 1978; Wertsch, 1997).

Topic-specific knowledge represents a teacher's knowledge of specific strategies for helping students comprehend specific science concepts. These strategies are divided into two categories: knowledge of activities and knowledge of representations. Knowledge of activities refers to knowledge of the "activities that can be used to help students comprehend specific concepts or relationships; for example problems, demonstrations, simulations, investigations, or experiments" (Magnusson et al., 1999, p. 113). Knowledge of representations, on the other hand, refers to "teachers' knowledge of ways to represent specific concepts or principles in order to facilitate student learning, as well as knowledge of the relative strengths and weaknesses of particular representations" (Magnusson et al., p. 111). This includes a teacher's ability to invent representations that promote student understanding of specific concepts and relationships. Examples of representations include illustrations, examples, models, and analogies. Shulman (1986) suggests, "Since there are no single most powerful forms of representation, the teacher must have at hand a veritable armamentarium of alternative forms of representation, some of which derive from research whereas others originate in the wisdom of practice" (p. 9). Consequently, Magnusson et al. (1999) posit, "An effective teacher must judge whether and when a representation will be useful to support and extend the comprehension of students in a particular teaching situation" (p. 112).

In summary, for this study, I am conceptualizing PCK as the transformation of various types of knowledge into a specialized type of knowledge for teaching that is the most powerful for teaching specific topics to specific students in specific contexts. In particular, PCK represents the transformation of one's subject matter knowledge, one's general pedagogical knowledge, and one's knowledge of the context. Additionally, I am conceptualizing PCK as a reflection of one's knowledge in four areas: curriculum, students as learners, assessment, and instructional strategies. Each of these components of PCK is directly informed by the fifth component of PCK, one's orientation to teaching science, and to greater or lesser degrees, all five components of PCK are interconnected. However, for the sake of theorizing, it can also be useful to focus on a specific component of PCK.

Finally, PCK represents one's knowledge that has been transformed for teaching specific ideas in powerful ways. However, a teacher may also possess knowledge that has not been transformed into PCK. For example, a teacher might use a certain representation for teaching a topic simply because this is the only representation that the teacher knows. I will refer to this type of knowledge as "general knowledge for teaching." In contrast, a teacher might use a specific representation to teach a specific topic to specific students because his or her orientation to teaching, knowledge of the students, knowledge of curriculum, knowledge of assessment, and knowledge of many possible representations all inform the choice of using a specific representation for the specific topic and specific students. This would represent PCK.

Teacher Learning

The development of teacher knowledge is undergirded by assumptions regarding how teachers learn. For example, a developmental model of teacher learning (Fuller, 1969; Fuller & Bown, 1975) adopts a behaviorist perspective on learning (Skinner, 1938; Watson, 1913) and portrays teachers as "progressing along a predetermined path in the development of their competence as teachers" (Loughran, 2007, p. 1043). From this perspective, learning is generally assumed to result from an individual's interactions with predetermined experiences from which specific, predicable learning outcomes are achieved. This perspective is reflected in "traditional" teacher preparation programs which view the teacher as a technician and emphasize the acquisition of basic and mechanical skills for teaching (Russell & Martin, 2007; Zeichner, 1993), and in one-size-fits-all professional development programs (Loucks-Horsley et al., 2003) in which teachers participate in identical experiences and are expected to develop nearly-identical understandings.

These perspectives stand in contrast to constructivist views of learning in which each learner is understood to be unique and complex and influenced by his or her background, culture, and needs (von Glasersfeld, 1995; Vygotsky, 1978; Wertsch, 1997).

Instead of simply responding predictably to experiences, the learner is thought to be responsible for his or her own learning (versus the instructor), and consequently, actively involved in the learning process. An individual's learning is therefore understood to be informed by his or her confidence, motivation, and willingness to engage in various experiences. In addition, learning is facilitated by interactions with more knowledgeable others who can provide instruction that pushes the learner beyond his or her current understanding without overwhelming the learner with information beyond the learner's developmental level. From the constructivist perspective as conceptualized by Piaget (1951, 1952), an individual is thought to construct understanding based on his or her personal experiences and conceptions of the environment by either incorporating the new experiences into his or her old experiences or by reframing the new experiences in light of current understandings. In the first case, the new experience is incorporated without the individual undergoing a change in his or her current understandings (simply adding to), while in the second case, current understandings undergo change as a result of the new experience. These understandings are consistent with the transformative model of PCK as described above, where PCK is understood as a dynamic and integrated type of knowledge that an individual develops over time and as the result of actively engaging in multiple experiences; some of which support and add to current knowledge while others require the teacher to reconsider current understandings.

As described previously, teachers typically engage in a variety of experiences intended to inform the development of their knowledge for teaching. However, the research literature on the development of teacher knowledge (Drechsler & van Driel, 2008; Halim & Meerah, 2002; Henze, van Driel, & Verloop, 2008; Lee & Luft, 2008) supports the conclusion that some experiences inform the development of knowledge while others do not. Clearly, this is inconsistent with a behaviorist perspective on learning. Consequently, it is from the constructivist perspective – that teachers are unique and complex and that they actively construct knowledge by incorporating new experiences into current understandings and by changing understanding in light of reflecting on new experiences, largely with the help of more knowledgeable others – that I am conceptualizing teacher learning.

Representations in Science

As described above, PCK represents the transformation and integration of multiple components of knowledge. In practice, these components do not act in isolation, but for the purposes of theorizing and description, it can be helpful to focus attention on a single component of PCK. For this study, I focus my attention on the instructional strategies component of PCK. More specifically, I focus on teachers' knowledge and use of representations. I have already described representations as viewed through the lens of PCK. In this section, I will describe how representations are understood in the discipline of physics and how I conceptualize representations in this study.

In general, a representation may be defined as "any of the widely diverse forms in which physical concepts may be understood and communicated" (Meltzer, 2005, p. 463). Implicit in this definition is the idea that physical concepts can only be understood and communicated using some form of representation. Or put another way, physical concepts are exactly that – concepts or abstractions, which by their very nature can only be expressed through some form of representation (Kilpatrick, Swafford, & Findell, 2001). In short, representations are essential for navigating a world full of abstractions. But because they are the product of human imagination, a variety of representations are possible regarding a particular concept. However, researchers have conceptualized the world of representations in math and science by developing categories intended to capture all possible representations. In this section, I will describe some of these categorizations.

Some researchers have tried to categorize representations by sorting them into broad categories. For example, Goldin and Shteingold (2001) conceptualize all representations as falling into one of two systems: *external* systems of representation and *internal* systems of representation. External representations are those representations of concepts or ideas that are expressed in forms available to others. Typically, these systems of representations are developed over time and used by a wide range of people. Examples include mathematical equations, algebraic expressions, and graphs. On the other hand, internal systems of representation are those representations of ideas that are created in an individual's mind for making meaning. As internal representations, these constructs are not expressed in forms accessible to others, but instead remain as ideas and conceptions that are useful to the individual for sense making. If the individual is able to articulate the ideas in a form accessible to others, these internal systems can be expressed externally.

Consequently, for researchers like Goldin and Shteingold (2001) who use a broad classification system, the distinguishing factors between certain representations are easily identified. However, these types of classification systems are limited in their ability to capture a wide range of variation or purpose. Using a different perspective, some researchers have developed classification systems that sort representations into narrower categories.

For example, Gilbert (2007) suggests that there are five *modes of representation*: 1) concrete or material, 2) verbal, 3) symbolic, 4) visual, and 5) gestural. Concrete modes of representation are those items that are typically produced using resistant materials. Examples include ball-and-stick models of chemical compounds and plaster representations of the earth's core. Verbal representations consist of spoken or written descriptions of entities and the relationships between them as well as the metaphors and analogies used to describe them. Symbolic modes of representation include mathematical symbols, formula, equations, and expressions. Visual modes represent ideas using graphs, diagrams, and animations and include 2D diagrams and 3D virtual models produced by computers. Finally, gestural modes of representation utilize movement of the body or its parts, such as moving one's hands to demonstrate the motion of an object.

Lesh, Post, and Behr (1987) suggest a classification system similar to that of Gilbert (2007). They suggest that there are five distinct types of representation systems: 1) experience-based scripts, 2) manipulatable models, 3) static figural models, 4) spoken languages, and 5) written symbols. Experienced-based scripts include knowledge that is "organized around "real-world" events that serve as general contexts for interpreting and solving other kinds of problem situations" (p. 33). Manipulatable models on those representations in which elements in the system "have little meaning per se, but the "built in" relationships and operations fit many everyday situations" (p. 33). Examples include number lines and arithmetic blocks. Static figural models include items such as pictures and diagrams that can be internalized as "images." Spoken language includes verbal articulations of ideas as well as specialized sublanguages related to domains like logic. Finally, written symbols include written words and phrases as well as specialized symbolic combinations such as equations.

The classification systems for representations proposed by Gilbert (2007) and Lesh, Post, and Behr (1987) attempt to sort representations into categories that capture a greater range of variation when compared to the system proposed by Goldin and Shteingold (2001). However, in all cases, it is clear that there is variation in the ways that one can conceptualize the representations used in math and science. This variation regarding what is and what is not a representation highlights a critical issue in any examination of representations – ultimately, all expressions of reality-as-perceived can be classified as representations. In a science classroom, this includes all spoken and written language, all letters and numbers, all drawings and sketches, all charts and diagrams, all scales and measuring devices, and all textbooks and digital media. In short, any form of communication in the classroom is ultimately a form of representation. Therefore, in an investigation into teacher knowledge and use of representations, it is necessary to define the parameters regarding what constitutes a representation and what constitutes ordinary communication.

For the purposes of this study, I am conceptualizing a representation as a symbol system that depicts a narrow slice of reality-as-perceived. In this sense, I am focusing my attention exclusively on external systems of representation as described by Goldin and Shteingold (2001). However, it is also necessary to concentrate on a more narrow range of external representations. Consequently, for this study, I focus on concrete, symbolic, visual, manipulatable, static figure, written, verbal, and gestural representations as they directly relate to a specific physics topic. In other words, I do not consider all forms of verbal and written and gestural representation that occur during a class period, but only those forms of external representation that the teacher uses for teaching a particular topic. This is in agreement with the Magnusson et al. (1999) conception of topic-specific representations.

Research Questions

The work of scholars in the areas of physics representations, teacher knowledge, and the development of teacher knowledge point to the importance of investigations focusing on the nature of the experiences that inform the development of teacher knowledge for using representations to teach particular topics in physics. A closer examination into the construct of PCK highlights that PCK can be understood as the transformation of various types of knowledge into a specialized type of knowledge for teaching. This specialized knowledge represents the most powerful knowledge for teaching specific topics to specific students in specific contexts and it results from a teacher's knowledge in five areas: orientations to teaching science, curriculum, students as learners, assessment, and instructional strategies. All of these components are interconnected, but focusing attention on one component and considering its interactions with the other four components can move our understanding of PCK forward. Specifically, focusing on the external representations that a teacher uses to teach particular physics topics improves our understanding of the knowledge that veteran teachers draw upon when using representations. Therefore, this study is focused on understanding and describing the experiences of veteran high school physics teachers that inform and promote the development of specialized knowledge for using representations to teach specific topics to high school students.

Overarching Research Question

The following overarching research question guided this study: Through what experiences do veteran 9^{th} grade physics teachers develop specialized knowledge for using representations to teach the topics of energy transformation and transfer?

Sub-Research Questions

Three sub-research questions arise from the overarching research question. The sub-research questions which guided the study are:

1. What specialized knowledge do veteran teachers have for using representations to teach energy transformation and transfer?
2. How does knowledge change over the teacher's career?
3. What experiences influence change in teacher knowledge?

CHAPTER TWO: LITERATURE REVIEW

As described in chapter one, the purpose of this study is to explore the experiences informing the development of veteran 9^{th} grade physics teachers' specialized knowledge for using representations to teach the topic of energy transformation and transfer. Consequently, this review of the literature is organized around three bodies of research: 1) supports for general teacher knowledge development, 2) development of PCK and 3) representations in physics education. These bodies of research correspond to various components of the research question.

First, this study is focused teacher experiences. As described in chapter one, teachers are typically provided with a variety of experiences and support structures intended to strengthen their knowledge for teaching throughout their careers. Therefore, in the first section of the review, I will describe the impact of these supports on the development of teacher knowledge and highlight the features of the supports identified in the literature as effectively supporting the development of teacher knowledge. In order to provide a more comprehensive overview of these support structures, the first section of the literature review will not focus exclusively on the development of PCK, but instead, on supports that facilitate the development of teacher knowledge in general (this may or may not be knowledge that informs an individual's PCK).

Second, this study is focused on specialized knowledge for teaching, or PCK. Consequently, in the second section of the literature review, I will narrow the focus of the review to studies that specifically explore the development of secondary science teachers PCK (versus general knowledge for teaching). The second section will conclude with a summary regarding the development of secondary science teachers' PCK.

Third, this study is focused on teachers' knowledge of using representations to teach topics in physics. Consequently, in the third section, I will explore the literature on representations in physics education and conclude with the claims that emerge from the review. At the conclusion of the literature review, I will make a case for conducting a study on the development of veteran high school physics teachers' PCK for using representations to teach the topics of energy transformation and transfer.

Supports for General Teacher Knowledge Development

The literature that speaks most directly to the experiences and support structures intended to strengthen a teacher's knowledge for teaching throughout his or her career can be divided into two areas that correspond to two time periods in a teacher's career. The two areas are: 1) induction programs and 2) professional development. These areas of research are outlined below.

Researchers generally refer to the beginning years of a teacher's career as the induction years. Although there is little consensus as to the exact length of the induction period, researchers generally discuss induction as the first two to five years of a teacher's career. During this time period, beginning teachers are often supported by some form of induction program. Consequently, the features of these induction programs serve as the basis for the first section of this literature review on the supports for the development of general teacher knowledge.

After the induction years (and oftentimes during), teachers typically engage in a variety of workshops, activities, and/or programs that are intended to support the development of their knowledge for teaching. In general, the literature refers to these experiences simply as in-service teacher professional development. Consequently, the professional development literature will serve as the basis for the second section of this literature review on the supports for the development of general teacher knowledge.

Induction Programs

The purpose, focus, and goals of induction programs vary widely, but in general, the goals include improving teaching knowledge and performance, promoting personal and professional well-being and attitudes, increasing teacher retention, and facilitating the transition to the culture of teaching (Huling-Austin, 1990). Common supports during the induction period include collaboration with colleagues, mentoring, collaborations with school district and university teacher educators, workshops and seminars, classroom observations and feedback, conference attendance, access to experienced science teachers, graduate courses, and access to curricular resources (Huling-Austin, 1992; Luft & Patterson, 2002; Smith & Ingersoll, 2004). As such, induction programs can range from simple programs that include a few of these supports during a relatively brief period of time (e.g., beginning of the school year) to highly structured, comprehensive programs that include a large number of supports over a period of several years (Smith & Ingersoll, 2004). In general, induction programs that concentrate on one-shot experiences at the beginning of a school year, followed by periodic follow-up meetings throughout the year, are limited in their ability to support the growth of beginning teachers (Britton, 2006). In contrast, comprehensive induction programs have been shown to promote the development of knowledge for teaching while also improving the retention of new teachers as well as their personal and professional well-being (Huling-Austin, 1990; Smith & Ingersoll, 2004).

As an example, Luft, Roehrig, and Patterson (2003) explored the impact of three different induction programs on the practices, beliefs, and experiences of 18 beginning secondary science teachers. Conducting a qualitative and quantitative analysis of a combination of interviews, observations, and teacher documents, the researchers concluded that the participants in the science-focused induction program (monthly workshops on science instruction, attended a regional science teacher conference, access to experienced secondary science teachers, observation and feedback from science faculty) implemented more student-centered inquiry lessons and held beliefs consistent with student-centered practices as compared to participants in a general induction program (a workshop focused on school procedures and management at the beginning of the year, follow-up workshops on general pedagogical issues throughout the year, access to mentors) and compared to participants who did not participate in an induction program at all (any mentoring was informal and from various colleagues).

In another study, Roehrig and Luft (2006) explored the impact of a science-specific induction program on the development of first-year science teachers' knowledge, beliefs, and practices. The induction program included monthly meetings with university and school district educators, visits to classrooms, trips to national and state-level conferences, and on-going electronic dialogue. Including teachers from four different types of teacher preparation programs (undergraduate k-8, undergraduate 7-12, M.Ed. with a science emphasis, and alternative certification) and conducting a qualitative analysis of participant interviews, observations of practice, and participant evaluations, the researchers concluded that the induction program supported the development of the participants' knowledge, beliefs, and practices, regardless of the participants' teacher preparation program. However, the type and level of support provided by the induction program differed depending on the participants' teacher preparation program.

These results highlight the potential impact of induction programs on the development of beginning teachers' knowledge and practice. These findings are supported throughout the literature, including the potential influence of mentoring on the development of teacher knowledge and practice (Eick, 2002; Rolheiser & Hundey, 1995), the potential impact of workshops on the development of teacher knowledge and practice (Britton, 2006; Luft & Patterson, 2002; Moir & Gless, 2001), and the potential influence of collaboration with colleagues (Gold, 1996; Huling-Austin, 1990, 1992). And although the specific content and organization of individual induction programs differ, a review of the literature reveals four features of effective programs.

First, comprehensive induction programs commit to a common vision that extends beyond new teacher retention to include goals related to the development of knowledge for high quality instruction, teacher orientation, teacher beliefs, teacher support, career learning, and knowledge about their content area (Britton, 2006; Luft & Patterson, 2002; Moir & Gless, 2001; National Science Teachers Association, 2009). Second, comprehensive induction programs require institutional commitment and support, largely through the allocation of adequate time and resources for the beginning teachers to engage in the various components of the program. Third, comprehensive induction programs make a time commitment to the entire induction process, ideally, more than one year. This commitment to a longer period of time acknowledges that the beginning years of teaching are a transitional phase and that transitioning to the new school culture takes time (Gold, 1996), regardless of the teacher preparation that the novice received during his or her pre-service education. Finally, comprehensive induction programs provide opportunities for collaboration (Borko, 2004; Loucks-Horsley et al., 2003; National Science Teachers Association, 2009). These include interactions with other novices that focus on sharing experiences, discussing successes and concerns, and learning from each other as well as collaboration between universities, school districts, and experienced teachers.

Professional Development

Throughout their careers, in-service teachers commonly participate in a wide range of professional development (PD) experiences, including seminars, workshops, conferences, and small- and large-scale professional development projects funded at the local, state, and national levels (Borko, 2004; Fishman, Marx, Best, & Tal, 2003; Loucks-Horsley et al., 2003). The prominent role that PD is thought to play in the development of in-service teachers' knowledge and practice is reflected in policy and national reform documents (National Council of Teachers of Mathematics, 1991; National Research Council, 1996; National Staff Development Council, 2001) and the potential for professional development to inform the development of a teacher's knowledge is widely documented (Birman, Desimone, & Porter, 2000; Borko, 2004; Garet, Porter, Desimone, Birman, & Yoon, 2001; Wilson & Lowenberg, 1991).

As an example, Fishman, Marx, Best, and Tal (2003) reported on the results of a PD project supporting a large-scale, standards-based systemic education reform in a large public school district. The PD focused on supporting sixth, seventh, and eighth grade science teachers' instruction regarding life science and physical science curriculum materials originally designed for smaller contexts that were "scaled up" for the large urban context. Following 40 teachers from 14 different schools, the researchers conducted and collected a combination of student artifacts, student pre- and post-tests related to the curriculum, teacher interviews regarding their attitudes and beliefs about the PD, observations of classroom teaching focused on evidence of PD characteristics, and teacher interviews after the observations. Using a constant comparative qualitative analysis along with statistical analyses, the researchers concluded that the PD workshop had a positive impact on the teachers' knowledge and beliefs about their teaching and on their classroom enactment and that the changes in the teachers' knowledge and beliefs translated into improved student performance.

As another example, Garet et al. (2001) explored the effects of various PD programs on science and mathematics teachers' instruction. Each of the PD programs was funded by the same source (Federal Elementary and Secondary Education Act), but the design and implementation of the individual PD programs was different. The researchers asked 1,027 teachers who participated in a variety of PD experiences to complete a survey regarding the changes in their knowledge, skills, and classroom practice as a result of their participation in the PD. The researchers then quantified the results of the survey based on characteristics of effective PD as identified in the literature, including, the type of PD (e.g. workshop, teacher research, etc), duration, collective participation (e.g., teachers from the same school or individual teacher from many schools), type of learning (active or passive), coherence to teacher's professional development (e.g., goals, district assessments, etc), and focus on content. Based on a least squares regression of the quantified survey data, the researchers concluded that PD that focused on content knowledge, opportunities for active learning, and coherence with other learning activities had a positive effect on teacher knowledge, skills, and classroom practice, and that through these features, the form of the activity, collective participation, and duration of the activity significantly affected teacher learning. These findings were supported by Desimone et al. (2002) in a larger follow-up study.

These studies highlight the potential for PD to inform the development of teacher knowledge and practice. However, the literature consistently supports that there is often a gap between the ideal image of effective PD as touted in the literature and in reform and policy documents when compared to the realities of actual PD programs and practice (Ball & Cohen, 1999; Loucks-Horsley et al., 2003; Putnam & Borko, 1997). Borko (2004) explains, "Each year, schools, districts and the federal government spend millions, if not billions, of dollars on in-service seminars and other forms of professional development that are fragmented, intellectually superficial, and do not take into account what we know about how teachers learn" (p. 3). These findings have prompted researchers and policy makers to explore and identify the components of effective PD programs that result in changes in teacher knowledge, teacher practice, and student learning. For example, Park Rogers et al. (2007) compared the views of effective PD held by 72 teachers and 23 PD facilitators representing nine different science and mathematics PD projects which were all funded by the same source (one state's Improving Teacher Quality Grants program). All of the PD projects were similar in that they each held 2-3 weeklong summer institutes where the teachers participated in hands-on, inquiry-based professional development projects. During the school year following the summer institutes, each of the projects conducted several weekend or school day visits. Each of the teachers and PD facilitators in the study participated in individual, semi-structured interviews at the end of their respective summer institutes centered on their characterizations of effective PD based on their previous and current experiences. Based on a qualitative, inductive analysis, the researchers concluded that both the teachers and the PD facilitators agreed on common characteristics of effective PD, specifically, that effective PD includes: 1) demonstrating activities and teaching strategies that apply to the teachers' curricular needs, as well as providing teachers with the resources necessary to easily implement the activities, 2) establishing opportunities throughout the PD project for teachers to experience activities from a student's perspective, and 3) developing a network of support for the teachers. A comparison of these findings to other research, policy, and reform documents reveals a high level of correlation.

For example, in their book on designing professional development for science and mathematics teachers, Loucks-Horsley et al. (2003) highlight characteristics of effective PD, which include providing opportunities for teachers to build their content and pedagogical content knowledge and examine practice, engaging teachers as adult learners in the learning approaches they will use with their students, and providing opportunities for teachers to collaborate with colleagues and other experts to improve their practice. The *National Science Education Standards* (National Research Council, 1996) address the issue of PD and include that PD should use inquiry, reflection, modeling, and guided practice, as well as provide regular and frequent opportunities for individual and collegial examination and reflection on teaching practice. The *Standards for Staff Development* (National Staff Development Council, 2001), suggest that among other things, PD programs should organize learning communities and align goals with school and district, provide necessary resources to support adult learning and collaboration, and model research-based instructional strategies. Viewed collectively, and in conjunction with the findings from Park Rogers et al. (2007), the following features emerge as characteristics of effective PD:

- Demonstrate/model activities and teaching strategies associated with the curriculum or PD content
- Provide teachers with the resources necessary to easily implement the curriculum or activities
- Establish opportunities for teachers to experience activities from a student's perspective
- Develop a network of support for the teachers, both with colleagues and PD facilitators

In the next section, I turn from the literature exploring the supports intended to promote the development of general teacher knowledge and focus specifically on the development of PCK.

Development of PCK

The literature specific to the development of PCK can be divided into two general categories: 1) pre-service teacher PCK development and 2) in-service teacher PCK development. The studies in this section of the review are limited to studies of secondary science teachers' PCK development.

Pre-service Teacher PCK Development

The focus of this present study is on the experiences of veteran teachers that inform the development of their PCK for teaching a specific topic. As discussed previously, research suggests that PCK develops primarily through classroom teaching experiences and the supports provided during in-service teaching (i.e., induction programs and professional development). However, a large portion of the research literature on the development of PCK is situated in the context of pre-service teacher education – a context in which individuals have not had access to induction programs or professional development. Therefore, the pre-service teacher PCK literature speaks to the impact of university methods courses and programs on the development of PCK. This literature is informed by the work of scholars in multiple science domains (e.g., chemistry, physics, biology). Consequently, for the purposes of a study exploring the PCK for teaching topics in physics, it stands to reason that a review of the literature focused on the development of PCK specific to teaching physics is more fitting due to the topic-specific nature of PCK. However, because the development of teacher knowledge is complex and multi-faceted, and because physics-specific studies are limited, a review of the literature from multiple science domains helps to paint a more complete picture of PCK development for science teachers.

The majority of the pre-service PCK literature highlights the connection between teacher education programs and the development of teacher's PCK. For example, Halim and Meerah (2002) investigated twelve pre-service physics teachers' PCK as a result of their experiences in a teacher education course (the nature and content of the course was not described). Data were collected using a questionnaire survey in which the teachers were to discuss how they would explain physics concepts to students and a follow-up interview connected to the responses to the survey questions. The researchers concluded that the pre-service teachers' PCK for promoting conceptual understanding was limited. Specifically, the teachers were unable to transform their understanding of basic physics concepts to forms accessible to students. Additionally, the researchers highlighted the connection between the teachers' limited knowledge of the physics content and their corresponding ability (or inability) to identify student misconceptions or select appropriate instructional strategies, suggesting that subject matter knowledge is a critical component to the development of PCK.

In another study, Veal, Tippins, and Bell (1998), explored the development of pre-service physics teachers' PCK as they engaged in a science methods class followed by field-based student teaching. The researchers used a qualitative case study analysis of two prospective physics teachers' responses to content-specific vignettes of teaching. The participants responded to the same teaching vignette and various points throughout their time in the curriculum class as well as at points during their student teaching. Examining the changes in the teachers' responses to the vignettes, the researchers concluded that the pre-service teachers developed a more student-centered approach to teaching and learning and that their PCK developed in response to their experience in the course. However, like the Halim and Meerah (2002) study, the content and structure of the science methods class and student teaching were not described. Consequently, it is difficult to determine which components of the methods course and student teaching contributed to the development of the teachers' PCK. A comparison of the two studies does, however, suggest that methods courses may or may not contribute to the development of a pre-service teacher's PCK.

In another group of studies, the researchers describe the nature and content of the methods courses or education program and the resulting impact on the development of PCK. For example, Sperandeo-Mineo, Fazio, and Tarantino (2005) explored the development of pre-service physics teachers' PCK as a result of their participation in a semester-long methods course/workshop focused on teaching physics through modeling (i.e., learning physics by constructing and using models). The course focused on helping the teachers make their mental representations explicit, allowing the teachers to experience similar learning environments to their future classrooms, supplying the teachers with pedagogical tools suitable for modeling instruction, and involving the teachers in activities stimulating hands-on learning and meta-reflection. Data were collected from 28 participants using a content knowledge admission test, two open-answer tests on models (pre- and post-test), and responses to worksheets from the course. Using a case study analysis, the researchers concluded that although the pre-service teachers entered the course with inadequate subject matter for teaching using a modeling approach, the methods course was "effective in guiding the teachers toward the construction of an appropriate PCK" (p. 260) for the specific topic of thermodynamics.

In another study, van Driel, De Jong, and Verloop (2002), investigated 12 pre-service chemistry teachers' development of PCK regarding their instruction on the relationship between macroscopic and microscopic properties. All of the teachers were participants in a teacher education program that focused on providing experiences for the teachers to teach under the supervision of a mentor teacher in a high school classroom as well as participation in a series of institutional workshops and meetings. Analyzing questionnaires, interviews, and audio recordings, the researchers concluded that the teachers developed an awareness of the need for explicit instruction on the relationship between macro and micro properties as well as the importance of careful and consistent language. The development of PCK was attributed to the teachers' experiences teaching the topic, to their participation in the workshop, and to the influence of their mentor teachers. This study lends more support for the potential impact of methods courses on the development of PCK and highlights the potential influence of teaching experience within pre-service education on the development of PCK.

In a similar study, De Jong, van Driel, and Verloop (2005) explored the impact of an experimental one-year introductory chemistry course module focusing on the use of particle models to help students understand the relationship between phenomena (e.g., physical and chemical processes) and corpuscular entities (e.g., atoms, molecules). Twelve pre-service chemistry teacher participated in a combination of “practice school” teaching experiences and institutional workshops during which they completed writing assignments, discussed ideas relating to teaching chemistry using particle models, and reflected on lessons. The researchers used these experiences and products as sources of data from which they performed an interpretative phenomenological analysis. The results of the analysis suggested that as a result of the workshops and teaching experiences, all of the teachers demonstrated deeper understanding of their students’ difficulties using particle models and half of the teachers “became aware of the possibilities and limitations of using particle models in specific contexts” (p. 947). Consequently, the researchers argued that the teachers further developed their PCK for using particle models to teach topics in chemistry. In a similar study, De Jong and van Driel (2004) explored the development of pre-service chemistry teachers’ PCK based on their experiences in a teacher education program in which the focus of the instruction was on learning from teaching as compared to learning of teaching. The researchers interviewed eight pre-service teachers before and after teaching selected chemistry topics and concluded that the teachers developed better understandings regarding student difficulties as well as the difficulties associated with teaching the selected topics. Like the preceding studies, these studies highlight the connection between the development of PCK and methods courses that couple coursework with teaching experiences.

In another study, Buaraphan, Vantipa, Srisukvatananan, Singh, Forret, and Tayloret (2007) the authors investigated the development of PCK of four pre-service physics teachers as a result of participating in a PCK-based physics methods course. During the course, students received explicit instruction on multiple components of PCK, observed and interviewed classroom teachers, participated in mock-teaching lessons, and engaged in micro-teaching experiences during which they taught specific topics to their peers. The researchers observed the teachers' instruction, conducted semi-structured interviews with the teachers before and after the micro-teaching, and examined related documents. Using a constant comparative method of analysis, the researchers concluded that the PCK-based methods course helped the participants to develop increased depth and breadth of understanding of PCK components. They attributed this development primarily to the participants' "multiple opportunities to teach specific topics to specific students within specific learning contexts, and to reflect on what they had learned from those experiences" (p. 284). However, the authors also noted that the participants had difficulty transferring their PCK from their micro-teaching contexts into actual classroom settings as a result of the differences between the two contexts. This finding that school context and culture have the potential to effect teachers' development of PCK is supported by other researchers (Cochran, DeRuiter, & King, 1993).

Viewed collectively, the studies highlighted above suggest that as a result of methods courses coupled with teaching experiences, pre-service teachers will develop PCK. However, as suggested by Buaraphan et al. (2007), the transfer of PCK from the teaching experiences connected to methods courses into other contexts may not always occur. This finding is supported in numerous studies that reveal the limited knowledge for teaching demonstrated by pre-service teachers, despite engaging in teaching experiences. For example, Friedrichsen, Abell, Pareja, Brown, Lankford, and Volkmann (2009) used qualitative interpretive research methods to compare the knowledge for teaching of teachers with teaching experience to those without teaching experience. Four prospective biology teachers in an alternative certification program completed a lesson planning task and a semi-structured interview about their lesson the biology topic of heritable variation. The researchers coded the plans and interviews through multiple PCK lenses and found that all of the teachers wrote similar lesson plans, regardless of prior teaching experience, drawing primarily on general pedagogical knowledge (PK) and subject-matter knowledge (SMK). However, the participants with teaching experience demonstrated more integration among PK components. The researchers concluded among other things that "teaching experience alone is not sufficient for building knowledge for teaching" (p 374) and that "teaching experience, in the absence of teacher education, supported the development and initial integration of PK components, but did not lead to PCK development" (p. 376). The authors highlighted the importance of reflection on teaching in developing PCK.

In another study, Veal and Kubasko (2003) used a qualitative case study approach to explore the different instructional strategies that eight secondary pre-service biology and geology teachers used when teaching the topic of evolution. Performing a qualitative content analysis using a combination of observation, semi-structured interviews, casual conversation, and document collection, the researchers found, among other things, that the pre-service teachers relied on direct instruction "due to their lack of knowledge about the students' backgrounds within a community and lack of topic-specific activities, labs, and analogies" (p. 351). Furthermore, the authors suggested that disciplinary subject matter knowledge directly influenced the choice of instructional strategies and the approach that the teachers took to teaching the same topic. Consequently, they concluded that subject matter knowledge is a prerequisite to developing PCK.

Taken together, the literature on the development of PCK in pre-service teachers is inconclusive. On one hand, it is evident that participation in methods courses and engagement in teaching experiences does not necessarily result in the development of PCK. On the other hand, it is evident that pre-service teachers can develop PCK as a result of their experiences in methods courses and teacher education programs, especially when the courses are connected to teaching experiences. In addition, the development of PCK appears to be connected to reflection on coursework and teaching, strong subject matter knowledge, and the specific teaching context in which the teaching occurs.

In-service Teacher PCK Development

Similar to the pre-service PCK literature, which focused on the development of PCK as a result of methods courses and teacher education programs, a number of studies in the in-service teacher PCK literature speak to the influence of activities commonly associated with induction programs as well as activities commonly associated with professional development. For example, Justi and van Driel (1998) explored the development of a beginning chemistry teacher's PCK for using models and modeling in the classroom. Using a case study approach, the researchers explored the teacher's knowledge development based on their participation in a professional development program that combined institutional meetings (focused on learning activities on the roles of models and modeling) with an action research project. The researchers concluded that as a result of the program, the teacher's PCK regarding students' ideas about models and their abilities to conduct modeling activities improved, substantially. This study supports the findings in the pre-service PCK literature regarding the potential impact of coursework on the development of PCK. In addition, the study highlights the influence of purposeful reflection (i.e., action research) on knowledge development.

In another study exploring the impact of professional development experiences on the development of PCK, Clermont, Krajcik, and Borko (1993) investigated the impact of a two-week chemical demonstration workshop on the development of PCK of in-service chemistry teachers identified as novices in terms of their knowledge and use of chemical demonstrations. The workshop focused on theory, modeling, practice, and feedback as they relate to the use of demonstrations in chemistry. The researchers used clinical interviews prior to and at the conclusion of the workshop to investigate the participants' PCK. The qualitative analysis of the interviews suggested that the participants made gains in their knowledge of using demonstrations and their ability to adapt demonstrations to particular contexts. The researchers concluded that PCK "can be enhanced through intensive, short-term, skills-oriented workshops" (p. 41). However, this claim was not evaluated in contexts outside of the workshop (i.e., in the teachers' own classrooms).

In another study exploring the impact of professional development experiences on the development of PCK, van Driel, Verloop, and de Vos (1998) used a qualitative approach to explore the development of PCK in 12 experienced high school chemistry teachers as a result of a topic-specific workshop. The participants attended a workshop focusing on the topic of chemical equilibrium during which they received instruction intended to enhance their PCK – specifically, their ability to recognize specific student preconceptions and conceptual difficulties and their use of interventions and strategies for promoting conceptual change. The workshop was designed using a constructivist approach in which the participants were provided both practical experiences and results of research. Using transcripts of audio recordings of the workshops and classroom lessons in conjunction with written responses to assignments from sessions, evaluative questionnaires, and student written responses to assignments, the authors concluded that the participants reconstructed their PCK. Specifically, results of a constant comparison analysis suggested that the participants' subject matter knowledge was transformed to promote student understanding for the particular topic. From this study, it is clear that professional development activities such as workshops can promote the development of PCK.

In contrast to the findings in the previous studies regarding the impact of professional development on the development of PCK, other studies have reported the ineffectiveness of professional development on the development of PCK. For example, Drechsler and van Driel (2008) explored the PCK of nine experienced chemistry teachers after their participation in a training course that focused on student difficulties and using models to teach selected topics in chemistry. Two years after the completion of the course, the teachers were asked to respond to transcripts of students' responses about their understandings of the topics. Additionally, the teachers were asked to complete story-lines describing their satisfaction with teaching the topics. The researchers concluded that although the teachers recognized student confusion and difficulties with the topics, only a few of the teachers actually adjusted their instructional strategies and their use of models to address the student difficulties. The results suggested that the training course did not serve to strengthen the connection between the teacher's knowledge of student difficulties and their corresponding choice of instructional strategies. Comparing these results with the results of the previous studies on various professional development programs highlights that professional development programs may or may not promote the development of PCK.

The findings in the previous section on the development of pre-service teacher PCK also suggested that subject matter knowledge is a prerequisite to developing PCK. However, studies in the in-service PCK literature suggest that possessing strong subject matter knowledge does not necessarily lead to the development of PCK. As an example, Lee, Brown, Luft, and Roehrig (2007) used a mixed-methods approach to explore the PCK and development of PCK of 24 beginning high school science teachers. All of the teachers were in their first year of teaching and all of the teachers were participants in one of four different induction programs (e-mentoring, general, intern, and science-specific). Each of the participants participated in a semi-structured interview at the beginning and end of the school year. The interviews were designed to probe for elements of PCK, especially knowledge of student learning and knowledge of instructional strategies. The interviews were then transcribed and coded using a coding rubric from which the PCK of each participant was assigned a score. The PCK scores were then analyzed using quantitative analysis procedures to determine changes in the levels of PCK. Based on the analysis, the authors concluded that none of the participants demonstrated significant changes in their PCK during the year and that all of the participants had limited or basic levels of PCK. From this study, it is evident that strong subject matter knowledge does not necessarily lead to the development of PCK. In addition, the results of the study bring to question the impact of supports associated with induction programs, such as mentoring, on the development of teachers' PCK.

In another study, Lee and Luft (2008) described PCK from the perspective of four experienced secondary science teachers. Using a case-study approach, the researchers asked the teachers to "characterize the required knowledge areas for teaching science in their classes" (p. 1348). In addition to semi-structured interviews, the teachers submitted lesson plans, participated in classroom observations, and wrote reflective summaries over the course of two years. Based on the development of codes and a constant-comparative analysis, the researchers concluded that all of the teachers conceptualized PCK as the knowledge for teaching science and that all the teachers conceptualized PCK as containing the following components: science, goals, students, curriculum organization, assessment, teaching, and resources. Additionally, the critical aspect of the teachers' knowledge was their "ability to access and emphasize the different components [of PCK] individually and simultaneously" (p. 1360). Each teacher also had a personalized representation that directed his or her instructional decisions and actions and the teachers explained that much of their knowledge for teaching was acquired through classroom experience. These findings support the idea that PCK develops with teaching experience but add that PCK develops over time and at different points throughout teachers' careers. When compared to the findings of Friedrichsen et al. (2009), it becomes evident that oftentimes, pre-service teachers have limited or minimal PCK while experienced teachers may have more developed (i.e., more integrated or interconnected) PCK. However, the PCK of different experienced teachers may look different from teacher to teacher.

As an example of the differences in PCK among teachers, Henze, van Driel, and Verloop (2008) investigated the nature and development of PCK in nine experienced high school physics teachers teaching the topic of "models of the solar system and the universe." The curriculum (and hence elements of the topic) was new to all of the participants. Each participant was interviewed at the end of his or her instruction on the topic every year for three years via semi-structured interviews based on four aspects of PCK (instructional strategies, learners, assessment, and curriculum). Based on transcription and coding of the interviews, the researchers concluded that the participants demonstrated two qualitatively different types of PCK. Type A PCK was oriented towards the content of the models while Type B PCK was oriented towards model content, model production, and thinking about the nature of models. The authors also concluded that the two types of PCK developed in qualitatively different ways. The development of Type A was mainly influenced by the teachers' interpretation of students' results on written examinations and reports on group work while Type B developed in such a way that the content of the different elements of PCK were consistently and dynamically related to each other and to the teaching of the specific topic. In general, development of Type A PCK was demonstrated by more sophisticated knowledge about instructional strategies while development of Type B was evidenced by mutual changes in knowledge about instructional strategies, knowledge about students' understanding, and knowledge about assessment. Knowledge about the goals and objectives of the learning and teaching for the topic (curriculum) did not change significantly. Additionally, Type B knowledge developed "in such a way that the content of the different elements [of PCK] were consistently and dynamically related to each other and to the teaching of Models of the Solar System and Universe" (p. 1339). Beyond the identification of the differences between individual teacher's PCK, this study also introduces the finding that the development of PCK can occur as a result of the introduction of a new curriculum.

This finding can be contrasted, however, to a study by Cohen and Yarden (2009) in which they explored the changes in junior high school teachers' PCK ten years after the publication of a new national (Israel) curriculum in which the topic of the cell was to be taught "longitudinally in conjunction with other study contents." The teachers in the study were expected to teach the topic of the cell longitudinally, but they were free to select from a variety of curricular materials and support structures (e.g., workshops). Analyzing data collected from 77 teachers that participated in a combination of focus groups and teacher workshops, the researchers concluded that in general, the teachers had only superficially changed the way that they taught the topic and did not demonstrate PCK for integrating the content with various levels of explanation (e.g., macro versus micro), despite demonstrating knowledge of their students' difficulties comprehending the concepts.

In summary, viewing pre-service and in-service PCK studies collectively, the following claims may be made regarding the development of secondary science teachers' PCK:

- Teaching experience plays a central role in the development of PCK. However, teaching experience alone does not result in PCK development. Reflection on teaching is a critical factor in the development of PCK.
- Subject matter knowledge is a prerequisite to developing PCK. However, subject matter knowledge does not necessarily lead to the development of PCK.
- Beginning teachers typically have minimal PCK while experienced teachers may possess more developed PCK.
- PCK develops progressively over time.
- PCK looks different from teacher to teacher.
- PCK development can be supported through professional development experiences.
- School context and culture have the potential to affect teachers' development of PCK.
- The introduction of a new curriculum may result in the development of teacher PCK

In the next section, I will turn to the literature on representations in physics. At the conclusion of that section, I will discuss the implications of the lines of research that comprised the literature review.

Representations in Physics Education

A review of the literature of representations in physics speaks to the ways that experts and students understand and utilize representations in physics, specifically, that experts hold deeper conceptual understandings about representations than students and these understandings can translate into different understandings about the nature and utility of representations. For example, in a qualitative study investigating the conceptions of models held by students and experts, Grosslight, Unger, Jay, and Smith (1991) conducted clinical interviews with 33 mixed-ability 7^{th} graders and 22 honors-level 11^{th} graders in order to explore students' conceptions of the "nature of models" (e.g., how models are made, what models actually represent) and their use in science. The student conceptions were then compared to the conceptions of four experts in the field. The experts demonstrated constructivist perspectives, including the idea that models are constructed representations that capture different theoretical perspectives, that there is a distinction between abstract and physical models, and that models are used for formulating and testing ideas about reality. The students, on the other hand, held the conception that models, although different in scale, are physical copies of "the real thing" (not representations of ideas about real-world ideas or events). Additionally, students did not espouse the idea that different models may be used to capture different theoretical views.

This study highlights the findings that not only do experts hold deeper conceptual understandings about representations, but that these understandings translate into different understandings about the nature and utility of representations. This difference in understanding between experts and students was also demonstrated in a study by Itza-Ortiz, Rebello, Zollman, and Rodriguez-Achach (2003). In this study, the authors drew attention to the idea that an expert's deep conceptual understanding and use of technical physics words (representations) sometimes results in misunderstandings for students because the students do not possess deep conceptual understandings regarding the nature and utility of the words for communicating ideas. Whereas students were unable to distinguish between everyday and scientific uses of words, the experts understood that certain everyday words have particular meanings in physics contexts – meanings that are powerful for understanding and communicating complex ideas. Additionally, the experts were able to differentiate between the different terms (representations) and connect the terms to the physics concepts. The result was that the students who could articulate between terms in different contexts and explain the physics meaning scored better on their exams when compared to their peers who could not. Like the Grosslight et al. (1991) study on models, this study demonstrates another example of how an expert can hold a deeper conceptual understanding about a representation when compared to a student and how this deeper understanding can result in different conceptions about the nature and usefulness of the representation in communicating ideas. To the expert, representations are powerful for understanding and communicating different theoretical perspectives and for formulating and testing ideas about reality. Students, however, do not view representations in these ways.

A second set of studies suggests that students have difficulties transferring between representations and determining how representations are similar or different from each other. Albe, Venturini, and Lascours (2001) used a qualitative approach to investigate how university students use mathematical representations when studying electromagnetism. The authors began by interviewing 50 pre-service science teachers about topics in electromagnetism, focusing on the relationship between, and the use of physical definitions and mathematical formula in electromagnetism. They then used the results to create a multiple-choice questionnaire, an open-ended questionnaire, and structured interview questions that they asked 64 physical science undergraduates to complete. Based on a qualitative analysis in which student responses were coded and categorized, the authors concluded that the students had difficulties transferring between mathematical and definitional representations. Furthermore, physical knowledge appeared to be fragmented (i.e., basic concepts in electromagnetism are not connected to each other), and generally, students were not able to bring together different elements of knowledge. Additionally, students had difficulties connecting mathematical formalisms (e.g., vectors, integral calculus) with physical descriptions of electromagnetism and student use of mathematics was almost entirely procedural, lacking clear connections to conceptual understanding.

In another study, Beichner (1994) investigated the ways in which students understand and utilize the information contained in graphs of objects in motion. The author designed and tested a 21-question multiple-choice test over concepts represented by kinematics graphs (position versus time, velocity versus time, acceleration versus time). The test required respondents to transfer between all three types of graphs and make appropriate interpretations of an object's motion from the graphs. Using a quantitative analysis, Beichner concluded that although the high school students had good understandings regarding the mechanics of graph structure (axis, origins, coordinates, etc), the students, in general, were not able to interpret the graphs, averaging only 40% on the multiple-choice test. Students had difficulty determining the ways in which switching between kinematics variables changes the appearance of the graph, calculating slope for lines that do not pass through the origin, distinguishing between the slope of the graph and the height of the graph, and solving problems using the area under the line. Overall, the students that were able to translate correctly from one graph to another had the highest scores on the test (and presumably better understandings of the kinematics graphs and concepts).

These studies highlight some of the difficulties that students demonstrate when charged with the task of transferring between representations and determining how representations relate to each other. For the students, the representations did not serve as tools for bringing deeper conceptual understandings to physical concepts, but instead, acted as chunks of isolated knowledge that were disconnected from big picture understandings.

A third set of studies suggests that helping students begin with what they know and working incrementally towards complex representations can result in deeper conceptual understandings for students. This finding is supported by three studies.

In the first study, Ambrose, Heron, Vokos, and McDermott (1999) redesigned their laboratory-based tutorials to specifically address common student difficulties and examined the impact on student understanding. The redesigned tutorial required that students work in small groups and build understandings about the EM diagram in a step-wise manner. The tutorial began with a pre-test designed to elicit student misconceptions, and then based on ideas that the students were already familiar with, the tutorial acted as a platform for students to develop an understanding of the EM diagram, incrementally. During the process, students were encouraged to work back and forth between diagrammatic and mathematical representations of the EM field, building understandings about the representations and making connections to the real-world phenomenon. The researchers assessed student understanding using several questions on the midterm and final exams on which the students had to interpret diagrams, make predictions, and justify solutions. Anywhere from 200 to 800 college students in introductory calculus-based and algebra-based physics courses took a combination of the post-test questions. A quantitative analysis of the results indicated that the student scores increased dramatically from pre-test to post-test (e.g., an increase from 10% correct on the pre-test to 85% on the post-test for a particular question) and that students scored as well or better on the post-test as physics graduate student Tas did on the identical pretest. The authors concluded that misunderstandings of the EM diagram were caused primarily by conceptual difficulties and that the modified tutorials helped address these conceptual difficulties. The result was that students learned how to relate both the representations and the concepts to real world phenomena.

In a second study, Van Heuvelen and Zou (2001) investigated the usefulness of a multiple-representation problem solving strategy for helping students solve work-energy physics problems. In the context of the study, the multiple-representation strategy involved students creating a series of qualitative representations based on a single physical process. Students were encouraged to first translate a verbal description (the problem or question) into a picture. Second, students used the picture to create energy bar graphs of the situation. Third, students used the bar graphs to generate qualitative mathematical equations that could then be used to solve quantitative problems. The primary objective of the strategy was to help students represent physical processes in multiple ways and to link intuitive physical representations to more abstract mathematical representations so that the students might develop deeper conceptual understandings and problem-solving strategies instead of using rote procedures to solve for unknown variables. The researchers used the strategy with 67 college students in a calculus-based introductory physics course for engineers. Using data collected from a free-response survey and a not-for-credit work-energy problem, the researchers concluded that the multiple-representation problem solving strategy was useful for helping students learn physics. Specifically, the students generally felt that the strategy helped them understand the energy concepts more deeply and to solve the related problems more effectively. The students also felt that the strategy helped them develop problem-solving expertise, and although the students constructed bar graphs less and less as they became more and more comfortable working with and solving these types of problems, 60% of the students solved the not-for-credit energy problem correctly, compared to 20% that received traditional instruction.

In a third study, Clement (1988) investigated the impact of a bridging-from-anchors analogy strategy on student conceptual change in three areas of mechanics (static normal forces, frictional forces, and Newton's third law). The study was framed by the assumption that prior to any formal instruction on a topic, students hold prior conceptions. Some of these conceptions are not consistent with current physical theory (alternative conceptions) and some of these conceptions are in agreement with current theory (anchoring conceptions). In order to investigate how analogies can be used to bring about conceptual change, a series of lessons on topics in physics were designed that incorporated bridging analogies (intermediate examples that share important features with the students' anchoring conceptions and the target content example, and therefore serve as a bridge between what is understood and what is not), cooperative learning discussion strategies, explanatory models (e.g., constructions that help students imagine a mechanism for how the target is like the anchor) and demonstrations or empirical experiences. These lessons were then taught to an experimental group of 155 high school students in a first-year physics course by teachers trained during a one-week summer workshop. Prior to and after the instruction, the students completed identical pre- and post-tests developed around common alternative conceptions. These tests were also given to a control group of 55 students studying their normal curriculum. Additionally, the students were videotaped and interviewed during the lesson. Using both quantitative and qualitative analyses, the author concluded that the experimental group had a larger average gain on the post-test (27.5%) in areas where persistent alternative conceptions existed when compared to the control group. Additionally, the students understood the anchoring examples, but did not see them as analogous to the target until after the bridging analogy, explanatory models, and demonstrations, suggesting that all three strategies played a role in fostering conceptual change.

All three of these studies highlight various ways in which instructors took explicit steps to help students develop deeper conceptual understandings by starting with student ideas and working incrementally towards complex representations. In all of these studies, the students developed deeper understandings of the physics concepts and learned to use representations as tools for facilitating the process. These studies highlight how instruction can play a role in narrowing the gap between student and expert understanding and utilization of representations.

A final set of studies suggests that the choice of representation used for instruction can result in deeper conceptual understandings for students. This finding is highlighted in three studies. For example, using a quantitative approach, Meltzer (2005) investigated that role that particular representations (e.g., verbal, diagrammatic, mathematical/symbolic, graphical) play in facilitating student learning of particular physics concepts. In the study, students in an algebra-based undergraduate physics course were asked to complete a series of quizzes. The first quiz contained a number of questions tied to concepts covered during the first semester of the course. Two of these questions focused on the same concept (Newton's third law) using two different representations. The first question focused on a verbal representation (story problem-type question), while the second question focused on a diagrammatic representation (vector-type question). A second quiz contained questions on electrostatic force while a third quiz focused on concepts tied to direct-current circuits. The concepts in these quizzes contained four different representations for each of the two concepts. The analysis revealed that some students had misconceptions regarding the details of particular representations (e.g., vector arrows) and that these misconceptions lead to incorrect answers. In some cases, although the students chose the incorrect representation in answering a question, they were able to verbally justify their answer, correctly. Meltzer concluded that students tended to give inconsistent answers to questions based on the same concept but asked using different representations. In other words, many students tended to answer questions correctly using a particular representation but answered incorrectly using a different representation. However, the students did not demonstrate any pattern of representation-related errors beyond a slightly higher error rate on graphical (bar chart) questions, when compared to verbal, diagrammatic, and mathematical questions.

In a second study, Monaghan and Clement (2000) conducted a qualitative investigation on the impact of different types of computer simulation feedback on student learning, problem solving, and model construction. The authors operated under the assumption that accurate conceptions of relative motion are difficult to develop, and specifically, that students have a difficult time developing mental models of motion events. The authors suggested that developing mental models of relative motion is facilitated by the construction of visual models and the resolution of these visual models with numeric models. In the study, 38 high school students were asked to participate in predict-observe-explain activities using computer simulations on the topic of relative motion. Half of the students interacted with simulations that provided animated feedback, while the other sixteen students received numeric feedback from their computer simulations. Based on a case study comparison using video recordings of the students interacting with the simulations, the authors found that although learning occurred in both student groups (as demonstrated on a relative motion diagnostic test), the students that had the animated simulation used mental imagery (e.g., self-projection, non-communicative (to a partner) depictive hand motions, verbs that convey spatial information) to solve problems while the other half used faulty mechanical algorithms (e.g., pattern recognition, numeric processing). Consequently, exposure only to numeric data resulted in misconceptions and misunderstandings, while the simulation data allowed students to conceptualize the phenomena.

In a third study, Podolefsky and Finkelstein (2006) used a quantitative approach to investigate how using analogies in the recitation portion of a large introductory college physics course influenced student reasoning and supported the generation of inferences when solving abstract and conceptually challenging electromagnetic (EM) wave problems. Each recitation section of approximately 25 students was randomly assigned to one of three groups. One group received an unmodified tutorial that was historically used in the recitation for introducing the topic of EM waves. This tutorial began with a description of the EM field. The second and third recitation groups received either a modified version of the tutorial that began with a description of sound waves, or a version that began with a description of waves on a string. These modified tutorials used the descriptions of sound waves and waves on a string as a starting point from which analogical comparisons about EM fields were generated. Besides the changes to the beginning, each version of the tutorial was identical. Following the tutorial, students were given a posttest on EM fields. Based on a quantitative analysis of student responses to the posttest, the researchers concluded that different analogies lead students to generate different ideas and understandings and that the representations were crucial to student reasoning and the promotion of certain analogical mappings. In short, student exposure to particular analogies resulted in students selecting particular answers. Because different analogies resulted in different answers (some correct, some not) the researchers suggested that the choice of representation when learning about particular concepts is important.

In summary, based on the reviewed studies, the following claims can be made about representations in physics:

- Teachers hold deeper conceptual understandings about representations than students and these understandings can translate into different understandings about the nature and utility of representations

- Students have difficulties transferring between representations and determining how representations are similar or different from each other

- Teachers can help students develop understandings about representations by beginning with what the student knows and working incrementally towards complex representations

- The choice of representation that a teacher uses for instruction can result in deeper conceptual understandings for students

These studies highlight the difficulties that both teachers and students bring to the task of using representations in physics instruction. Clearly, teachers can develop knowledge for helping students overcome the challenges of understanding representations in scientifically accurately ways. However, based on the review of the physics representation literature, beyond formal professional development experiences (e.g., workshops) and reflection on teaching experiences, it is unclear as to what types of experiences inform the development of this knowledge. Additionally, based on the review of the induction, PD, and PCK literature, it is unclear what experiences help teachers transform the knowledge that they do have for using representations into other teaching contexts. And despite the studies that do exist regarding induction programs, professional development, and the development of PCK (as highlighted above) numerous researchers have suggested that the current research literature base on science teacher knowledge development is inadequate (Abell, 2007, 2008; Friedrichsen et al., 2009; Henze et al., 2008; Lee et al., 2007; van Driel et al., 2002; van Driel et al., 1998). More specifically, there are few studies that have examined the development of PCK of secondary physics teachers, and it appears that there are no published studies exploring the development of PCK regarding the use of representations in high school physics. Because of the topic-specific nature of PCK, and the centrality of representations in physics, this research study investigating the experiences informing the development of veteran 9th grade physics teachers' PCK for using representations to teach the topic of energy transformation and transfer is needed. Therefore, I explored the following question: Through what experiences do veteran 9th grade physics teachers develop specialized knowledge for using representations to teach the topics of energy transformation and transfer? In addition, I explored the following sub-questions:

1. What specialized knowledge do veteran teachers have for using representations to teach energy transformation and transfer?

2. How does knowledge change over the teacher's career?

3. What experiences influence change in teacher knowledge?

CHAPTER THREE: THE RESEARCH PROCESS

Design of the Study

Both qualitative and quantitative approaches to inquiry permeate the field of educational research. However, the approaches are distinct in both the types of questions that the researcher aims to address as well as the methods by which the inquiry is conducted (Denzin & Lincoln, 2005; Hatch, 2002; Patton, 2002). Quantitative studies draw conclusions by examining the relationships between sets of variables using statistical analyses. In contrast, qualitative studies tend to focus on the perceptions, attitudes, knowledge, beliefs, and/or processes that reflect the ways in which individuals navigate their everyday lives (Glesne, 1999). Qualitative approaches acknowledge and account for varying levels of interaction between participant and researcher and promote the investigation of phenomena in natural settings, relying heavily on interviews and observations. Because I am investigating the development of teacher knowledge regarding a particular phenomenon based on the teachers' past and present experiences, a qualitative approach is most appropriate for this study.

Research Tradition

I will explore the development of teacher knowledge using phenomenography as my research tradition. Phenomenography is broadly described as "research which aims at description, analysis, and understanding of experiences; that is, research which is directed towards experiential description" (Marton, 1981, p. 180). Ference Marton offered this articulation of phenomenography nearly 30 years ago at phenomenography's infancy. However, this description does little to highlight phenomenography's philosophical underpinnings or to distinguish it from a range of qualitative approaches to research that focus on the experiences of others (e.g., ethnography, phenomenology). Consequently, in the following section, I will describe phenomenography in terms of its philosophical assumptions and the characteristics that distinguish it from similar research traditions. In doing so, I hope to bring clarity to that which phenomenography is, and to that which phenomenography is not. I will conclude this section with a discussion of the outcomes of phenomenographic research and the ways in which these outcomes are informed by the phenomenographic characteristics. The characteristics that distinguish phenomenography as a research tradition include: 1) philosophical assumptions, 2) participant conceptions of phenomena, 3) participant recollection, 4) focus on variation, and 5) finite number of categorizations.

Philosophical Assumptions

Phenomenography's focus on the experiences of individuals reflects its philosophical assumptions. Regarding the nature of reality (ontology), phenomenography holds that "there is only one world, a real existing world that is experienced and understood in different ways by human beings" (Marton & Booth, 1996, p. 537). A key component of this ontology is the emphasis on there being "one world." Phenomenographers have described this as a *non-dualist* perspective (Marton, 1988; Marton & Booth, 1996, 1997; Richardson, 1999; Uljens, 1996). From the non-dualist perspective, this "one world" is thought to be both objective and subjective at the same time. However, phenomenographers do not hold to a positivist understanding of a world and reality that is "out there to be studied, captured, and understood" by individuals that are capable of knowing how the world is "really ordered" (Hatch, 2002, p. 13). Instead, this one world is viewed as a relationship. Marton and Booth (1997) elaborate on the non-dualist perspective:

> There is not a real world "out there" and a subjective world "in here." The world is not constructed by the learner, nor is it imposed upon her; it is constituted as an internal relation between them. There is only one world, but it is a world that we experience, a world in which we live, a world that is ours" (p. 13).

From this perspective, reality is considered to exist entirely through the way in which individuals experience it. Consequently, it has been argued that one cannot meaningfully talk about unexperienced reality, as the only reality that exists is inextricably linked to experience (Marton & Neuman, 1989; Uljens, 1996). The essence of reality is captured entirely by the whole range of individual experience and as such, reality is fully explained by, and cannot extend beyond human experience. Therefore, epistemologically, phenomenology holds that what can be known is represented by individual experiences. Knowledge is therefore a reflection of these experiences and the similarities and differences in these experiences (Svensson, 1997). In this sense, phenomenography's epistemological perspective is represented by its ontological position (Richardson, 1999; Uljens, 1996).

Participant Conceptions of Phenomena

Because of the philosophical assumptions regarding the connection between experience and reality, phenomenography posits that individual experiences provide direct access to reality. Or, put another way, reality is considered to exist through the way in which a person is related to, or more specifically, perceives himself or herself to be related to the world (Uljens, 1996). Therefore, a central characteristic of phenomenographic research is the focus on the participant's conceptions of a particular phenomenon, and not on the phenomenon itself (Marton, 1981, 1986, 1988, 1994; Marton & Booth, 1996; Patton, 2002; Richardson, 1999; Schmitt, 1967; Svensson, 1997). This focus on individual conception of phenomena stands in contrast to research traditions (especially quantitative approaches) that deemphasize the conceptions of the participant in favor of a more "objective" position. However, phenomenography blurs the notion of objective and subjective worlds and instead takes what Marton (1981) coined a "second-order perspective" (p. 175). From this second-order perspective, the researcher makes "statements about people's ideas about the world (or about their experience of it)" (p. 178) as opposed to a "first-order perspective" in which the researcher orients himself or herself towards the phenomenon and makes a statement about it. From the second-order perspective, the person and the world are considered to be "internally related" (p. 175) and therefore, descriptions of reality stem directly from the accounts and conceptions of the participant regarding the ways in which he or she experience the phenomenon.

Participant Recollection

The emphasis in phenomenography is on the conceptions of the participants – conceptions that the researcher can only access through the participants' self-reports of experience. Consequently, phenomenography hinges on the recollection and self-report of the participants and takes the participants' accounts at face value (Patton, 2002; Richardson, 1999). This stands in contrast to research traditions such as ethnography (e.g., van Maanen, 1996) which typically take a skeptical attitude towards participant responses. Therefore, observation serves as a foundation for building commonality from which the researcher and participant can talk about his or her experiences, not as a source of verification of the participant's accounts. Furthermore, the time period between the participant's experience and his or her report of the experience is inconsequential in terms of articulating his or her reality. Instead, the participant's conceptions about an experience are simply described in light of his or her current context (Marton, 1981, 1986, 1988, 1994; Marton & Booth, 1996, 1997; Marton & Saljo, 1984; Richardson, 1999). The participant's self-report is therefore a kind of situated, restricted, and focused re-creating of his or her experiences (Uljens, 1996) which become his or her present reality. A description of context is therefore an essential component of a phenomenographic study.

Focus on Variation

The focus in phenomenography is on the reported experiences of others, and in a broad sense, qualitative research that focuses on the experiences of others can have one of two general objectives – identifying a singular way of experiencing a phenomenon that is common to all individuals, or highlighting the various ways in which a phenomenon can be experienced. For instance, in phenomenology (e.g., Husserl, 1931; Schmitt, 1967), the focus is on identifying the "essence" of a particular phenomenon. Patton (2002) explains that "phenomenology asks for the very nature of a phenomenon, for that which makes a some 'thing' what it is – and without which it could not be what it is" (p. 104).

Conversely, in phenomenography, the focus is on finding the variation in people's experiences (Marton, 1981, 1986, 1988, 1994; Marton & Booth, 1997; Marton & Saljo, 1984; Richardson, 1999; Uljens, 1996). This variation has been described as the "complex of possible ways of viewing various aspects of the world" (Marton, 1981, p.

197). Therefore, the focus is not on articulating one singular way in which people experience a phenomenon, but instead on indentifying the variation and qualitative differences that distinguish and differentiate the phenomenon for each individual. So whereas in phenomenology the "essence" is understood as being a structure of the phenomenon (Uljens, 1996), in phenomenography, the "essence" (although phenomenographers do not typically use this term), and that which the researcher seeks to articulate, is the variation in conceptions of the phenomenon as communicated by a group of individuals. In short, the focus is not on the one common characteristic of individual experiences, but on the total variation in individual experiences. This is described as phenomenography's theory of variation.

Finite Number of Categorizations

A discussion about the "total variation" brings to question the possibility of ever being able to capture all of the possible variation that might exist regarding individual experiences with a particular phenomenon. In fact, early in the history of phenomenography, Marton (1978) argued that there were an infinite number of possibilities regarding the ways in which a phenomenon could be experienced. Therefore, the notion of ever being able to characterize all of the variation in people's experiences with a phenomenon was dismissed. In time, however, Marton and his colleagues retracted this notion in favor of the idea that "phenomena are usually experienced or conceptualized in a finite and relatively limited number of qualitatively different ways" (Marton, 1981, 1986, 1988, 1994; Marton & Booth, 1997; Richardson, 1999, p. 61). This position was both consistent with empirical findings (e.g., Gibbs, Morgan, & Taylor, 1984; Martin & Ramsden, 1987; van Rossum, Deijkers, & Hamer,

1985) and pragmatic in terms of reporting findings. It is from this position then – that there are a qualitatively limited number of ways in which individuals experience or conceptualize a phenomenon – that phenomenographic research is conducted.

Categories of Description

This section began with a general description of phenomenography: "Research which aims at description, analysis, and understanding of experiences; that is, research which is directed towards experiential description" (Marton, 1981, p. 180). These descriptions, analyses, and understandings are informed by the aforementioned characteristics of phenomenology. All of these characteristics culminate in what has been described as the most important result of phenomenographic research (Marton, 1986), specifically, phenomenography's *categories of description* (Martin & Ramsden, 1987; Marton, 1981, 1986, 1988, 1994; Marton & Booth, 1996, 1997; Marton & Neuman, 1989; Marton & Saljo, 1984; Patton, 2002; Richardson, 1999; Svensson, 1997; Uljens, 1996). These categories of description (sometimes referred to as an "outcome space") capture the variation in a group of participants' conceptions of their experiences regarding a particular phenomenon. These categories reveal something distinct about a particular way of experiencing an aspect of the world (Marton & Booth, 1997) and they are based on a collective analysis of individual experiences. The categories of description are unique, however, in that they emerge from participant responses, but are considered collectively as transcending any particular participant's individual conceptions. Marton (1981) explains this position:

> Conceptions and ways of understanding are not seen as individual qualities. Conceptions of reality are considered rather as categories of description to be used in facilitating the grasp of concrete cases of human functioning. Since the same categories of description appear in different

> situations, the set of categories is thus stable and generalizable between the situations even if individuals move from one category to another on different occasions. The totality of such categories of description denotes a kind of collective intellect, an evolutionary tool in continual development… In talking about categories of description, then, we "bracket" the dynamic-activity perspective and we consider the categories almost as if they were "frozen" forms of thought" (pp. 177, 195).

From this explanation, we see that although the data represent the active process of participants recalling their conceptions of experiences regarding some phenomenon, the findings, or categories of description, are viewed as a collection of all of the various participants' conceptions of experiencing a phenomenon. Consequently, the categories of description do not reflect the entirety of any one individual's conceptions. It is important to note, however, that although it is assumed that there are a finite number of ways of experiencing a phenomenon, the categories of description are not assumed to represent an exhaustive system for describing variation in the ways of perceiving a particular aspect of the world (Marton & Booth, 1997). Instead, the categories of description are considered to be as complete as possible in describing the variation in a particular group of participants, at a particular point in time, representing a particular group of people. It is from this perspective then – that the categories of description represent a group of individuals in a defined context – that the results of phenomenographic research are said to be generalizable, provided the generalizations are applied to groups from a similar context (Åkerlind, 2002; Cope, 2004). Ultimately, it is up to the reader to determine the generalizability of the findings to the group in which they are interested.

In summary, phenomenography aims to describe, analyze, and understand the experiences of others in regard to a particular phenomenon, based on the conceptions of the participants, with the ultimate goal of describing the distinct ways in which people experience some aspect of the world. Phenomenography is therefore an appropriate choice for this study on the development teacher knowledge, which is guided by the overarching research question: Through what experiences do veteran 9th grade physics teachers develop specialized knowledge for using representations to teach the topics of energy transformation and transfer? In addition, I explored the following sub-questions:

1. What specialized knowledge do veteran teachers have for using representations to teach energy transformation and transfer?

2. How does knowledge change over the teacher's career?

3. What experiences influence change in teacher knowledge?

Phenomenography is well suited for this study because of its focus on participant conceptions of phenomena, the emphasis and value placed on participant recollection, its assumption about the world being understood differently by individuals, and the usefulness of its end product in helping us better understand a particular phenomenon. These features will be highlighted in the following sections that describe the context, participants, data collection, data analysis, researcher role, limitations, and significance of this study investigating the development of experienced 9th grade physics teachers' knowledge for using representations to teach the topics of energy transformation and transfer.

Context of the Study

This study was conducted with experienced science teachers who work for a large school district in the state of Missouri. All of the teachers involved in the study are veteran (15+ years of teaching) 9th grade physics teachers that teach the topic of energy transformation and transfer. The study builds on the work of the Re-SMAR^{2}T project at the University of Missouri.

Re-SMAR^{2}T

This study builds on the work of the Re-SMAR^{2}T project (Researching Science and Mathematics Teacher Learning in Alternative Certification Models) (Abell, 2006) at the University of Missouri. Re-SMAR^{2}T is a National Science Foundation-funded research project (#0553929) focused on examining science and mathematics teacher learning in the context of an alternative certification program that employs two different models of field-based preparation. The project uses the Magnusson et al. (1999) model of PCK as a lens through which to view teacher learning. The model guides both data collection and analysis. The Re-SMAR^{2}T project focuses on teachers in their first years of teaching. However, the project team has also discussed the merit of exploring the PCK of experienced teachers. It is within this context that this study takes place.

School District and Classrooms

Westwood School District (pseudonym) serves approximately 16,400 students, k-12 (Missouri Department of Elementary and Secondary Education, 2007) and is divided into 20 elementary schools (k-5), three middle schools (6-7), three junior high schools (8-9), and 2 high schools (10-12). The teachers in this study all teach 9th grade physics at the junior high level but at two different junior high schools. Both schools operate on a seven-period day and each period is 50 minutes long. The class sizes that were observed ranged from 20 to 23 students. Each classroom is equipped with a *SMART Board* (an interactive whiteboard that allows the teacher to digitally write or draw while simultaneously projecting an image from a computer) and a data projector. Each classroom was also equipped with 12 to 14 two-person lab tables organized into rows.

A TIME for Physics First

Prior to 2006, the Westwood School District followed the traditional U.S. model of sequencing science courses in which students take a general physical science course in the 9th grade, followed by biology in the 10th grade, chemistry in 11th grade, and an elective (usually physics) in the 12th grade (Sheppard & Robbins, 2005). In 2006, the school district adopted a new science sequence in which physics is taught in the 9th grade. This move was made in conjunction with a professional development project aimed at introducing Physics First in Missouri schools (Torres, 2006). The project was funded by the Missouri Department of Elementary and Secondary Education and housed at the University of Missouri. The project, *A TIME for Physics First* (Academy for Teachers Inquiry and Modeling Experiences for Physics First), provided participating teachers with a research-based physics curriculum, summer professional development in scientific inquiry and modeling methods, in-class mentoring throughout the school year, support from professional learning communities (PLCs), and follow-up sessions and conferences. The teachers who participated in this study were all participants in the Physics First professional development from 2006-2009 and currently teach 9th grade physics in the Westwood School District. In addition, all of the teachers in this study taught 9th grade physical science prior to the introduction of 9th grade physics to the district.

Energy Transformation and Transfer

The topics of energy transformation and transfer was selected for three reasons. First, because the study is focused on investigating the development of teacher knowledge for using representations, it was critical to select a topic that is traditionally representation-rich. The Physics First curriculum from which the teachers based their lessons contains the following external representations: student sketches of instances/scenarios/before-after cases, handout/lecture material sketches of instances/scenarios/before-after cases, written descriptions of instances/scenarios/before-after cases, manipulatives (e.g., flashlight, windup toy, spring car, etc), photographs, symbols (e.g., E_g, E_{el}, E_k), symbolic equations (e.g., $E_{total} = E_k + E_g$, $\Delta E_g = (mg) \Delta y$), word and symbol combinations (e.g., System: the box + Earth + ground), pie chart, bar charts, matrix, shapes (direction arrows, vector arrows), work in/out of system (arrow in/out of "system circle"), line graphs, real-life examples (e.g., pitching a baseball), force diagrams, units (e.g., N, m, J), simulations, digital readouts, and vocabulary.

Second, I selected the topics of energy transformation and transfer because they were the first topics of instruction for the new school year. Consequently, I was able to observe and ask questions about why and how representations were introduced. This was important as some representations (e.g. equations) are used in the teaching of multiple topics. These representations will become second nature for students as they progress though topics. Observing the introduction of these topics allowed for more fruitful observations and interviews.

Third, I selected the topics of energy transformation and transfer because the concepts were taught prior to the introduction of Physics First to the school district (i.e., energy transformation was historically taught in freshman physical science). Consequently, the teachers had a long history of teaching the topic to 9th grade students.

Participants

The focus of this study was on the development of veteran 9th grade physics teachers' knowledge for using representations to teach the topics of energy transformation and transfer. The question therefore necessitated participants who are: 1) veteran (15+ years) teachers, 2) currently teaching physics to 9th graders, 3) currently using representations in their teaching, and 4) currently teaching the topics of energy transformation and transfer. Therefore, the participants in this study had to meet these four criteria. In addition, this study investigated the development of knowledge for using representations to teach a specific topic. Therefore, it was essential that the participants had a history of teaching the topics (criterion 5). Because the school district only started offering 9th grade physics in 2006, the teachers in this study also needed to have taught the topic of energy transformation to 9th graders at some point in the past, most likely, in 9th grade physical science (criterion 6).

I shared these six criteria with the science coordinator for the school district and asked her to provide me a list of teachers that meet these criteria. She provided me with a list of six teachers who would be viable candidates for the study. However, given the time-intensive nature of the data collection, and the fact that all of the 9th grade physics teachers in the school district teach the topic of energy transformation at the same time (first topic of the fall semester), the study was limited to three participants.

For the final selection of participants, I selected three participants based on logistics, specifically, the observations and interviews had to be coordinated so that it was possible to observe all three teachers every day that they taught and interview each teacher twice a week. For this reason, I wanted to select teachers that were in the same building and/or at schools within a short driving distance of each other. Ultimately, two teachers from one school and one teacher from a second school agreed to participate in the study. Each participant was given a $400 stipend for their participation.

Jake

Jake has taught in the Westwood School District for 26 years. After graduating with a B.S. in science education through a collaboration between two Missouri colleges in 1984, Jake got a job teaching 9th grade science (earth science, life science, health, and physical science) in the Westwood School District. During his first couple of years teaching, Jake also coached two sports. His primary source of professional development during this time was collaboration with and observation of veteran teachers in his building. Jake continued to teach and coach for twenty years, up until 2005. During that time, Jake developed a Physics and Engineering course through collaboration with one of the school's shop teachers. As this course evolved, Jake developed partnerships with the engineering and education departments at a nearby university. Through these partnerships, Jake explored applications of his Physics and Engineering course (e.g., exploring physics using Legos, Physics for Girls, student presentations at the university). In 1997, Jake earned his Master's degree in information science and technology from a nearby university. During this time, Jake also served as the science department chair and participated in a variety of professional development experiences including coursework at a nearby university (e.g., teaching methods, lesson design, backwards design). In all, Jake has his Master's plus 75 credit hours of additional coursework or professional development. In 2005, Jake quit coaching and in 2006 enrolled in the Physics First academy as the school district made the switch to 9th grade physics. Jake has continued to teach 9th grade physics and also serves as an instructor during the summers for another version of the Physics First project (with the same name – *A TIME for Physics First*), which focuses on a similar curriculum but emphasizes teacher leadership in secondary school physics departments.

Findlay

Findlay has been teaching in the Westwood School District for 15 years. She graduated from a state university in Missouri in 1994 with a B.S. in chemistry education and 18 hours of university physics. She is currently one class away from her Master's degree in education. Findlay got her first teaching job in 1995 teaching 7th grade general science in the Westwood School District. The next year, she moved up to the 9th grade classroom to teach physical science (one semester of basic chemistry, one semester of basic physics). During her first years of teaching, Findlay was involved in a wide range of professional development experiences including seminars on classroom management and content-related field trips to explore the science behind various municipal services (e.g. water treatment plant, power plant, landfill). Additionally, Findlay collaborated with veteran science teachers in her school to plan instruction and observe their teaching. She did this everyday during her planning period and/or after school for two years. Findlay continued to teach 9th grade physical science (honors and non-honors) for the next eight years, up until 2006. During that time span her professional development included collaboration with teachers in grades 10-12 (to work on alignment of the curriculum), energy programs with the local utility company (activities for students related to energy conservation), Saturday science programs (attending lectures, student presentations), graduate level courses (in education and administration), literacy seminars, and a summer Physics for Girls institute at a nearby university. In 2006, Findlay signed up for the Physics First academy in response to the district's decision to teach physics at the 9th grade level. She participated in the Physics First academy for three years and has taught 9th grade physics since. She has also signed up for another version of the Physics First project (with the same name – *A TIME for Physics First*), which focuses on a similar curriculum but emphasizes teacher leadership in secondary school physics departments.

Allie

Allie has been teaching in the Westwood School District for 19 years. After student teaching in an urban setting and graduating with a B.S. in English and biology education from a state university in Ohio in 1990, Allie applied for a job teaching 8th grade science in the Westwood School District. During her first years in the district, Allie was involved in a variety of professional development experiences including seminars on cooperative learning, learning styles, differentiation, and standardized-test preparation. She also had a mentor with whom she informally planned, observed, and reflected. In 1995, Allie started teaching 9th grade physical science (one semester of basic chemistry, one semester of basic physics) and continued in this position until 2005. During this time period, Allie served as the science department chair for her school, participated in the district Accelerated Schools program (looked at the vision and goals of the school, worked on improving student achievement, developed goals that could be measured, etc), participated in summer professional development focused on physics instruction through a nearby University (physics content, teaching strategies, equipment), participated in the introduction of the Behavior Intervention Strategies Team (BIST) in the district, and worked closely with her professional learning community (examining student data, planning instruction, looking at the curriculum, etc). In 2006, the district made the decision to move to Physics First so Allie decided to also make the switch to teaching 9th grade physics. She participated in the Physics First summer academy for three consecutive years and has taught 9th grade physics ever since.

Data Collection and Management

The purpose of a phenomenographic study is to explore the conceptions that individuals have of their experiences in relation to some phenomenon. Consequently, the data for phenomenographic studies take the form of people's descriptions and accounts of their experiences, obtained primarily through "semi-structured, individual, oral interviews using open-ended questions" (Marton, 1986, 1994; Marton & Booth, 1997; Richardson, 1999, p. 64). Thus, the primary data for this study was a series of semi-structured interviews. However, Marton (1986) also suggests that sources such as observations and written responses can serve as additional means by which a researcher can understand participant's conceptions, although these media ultimately "have the same evidential status as oral accounts" (Richardson, 1999, p. 64). Nevertheless, data sources beyond the semi-structured interviews can serve to inform the interview questions and help promote the participant's self reflection and "meta-awareness" (Marton & Booth, 1997; Uljens, 1996, p. 129) of his or her experiences. Consequently, for this study, I used the following data sources (see table 1, figure 3): 1) work history and professional development interview, 2) work history and professional development timeline, 3) unit/lesson plans, 4) pre-observation interview, 5) classroom observation with video, and 6) stimulated-recall interviews.

Table 1

*Sub-Questions and Data Sources. **P**: Primary Data Source, **S**: Secondary Data Source Used to Answer the Research Questions*

Sub-questions	Work history and professional development interview	Work history and professional development timeline	Unit/ lesson plans	Pre-observation interview	Classroom observation w/ video	Stimulated-recall interviews
1. What specialized knowledge do veteran teachers have for using representations to teach energy transformation?	S	S	S	P	S	P
2. How does knowledge change over the teacher's career?	S	S				P
3. What experiences influence change in teacher knowledge?	S	S				P

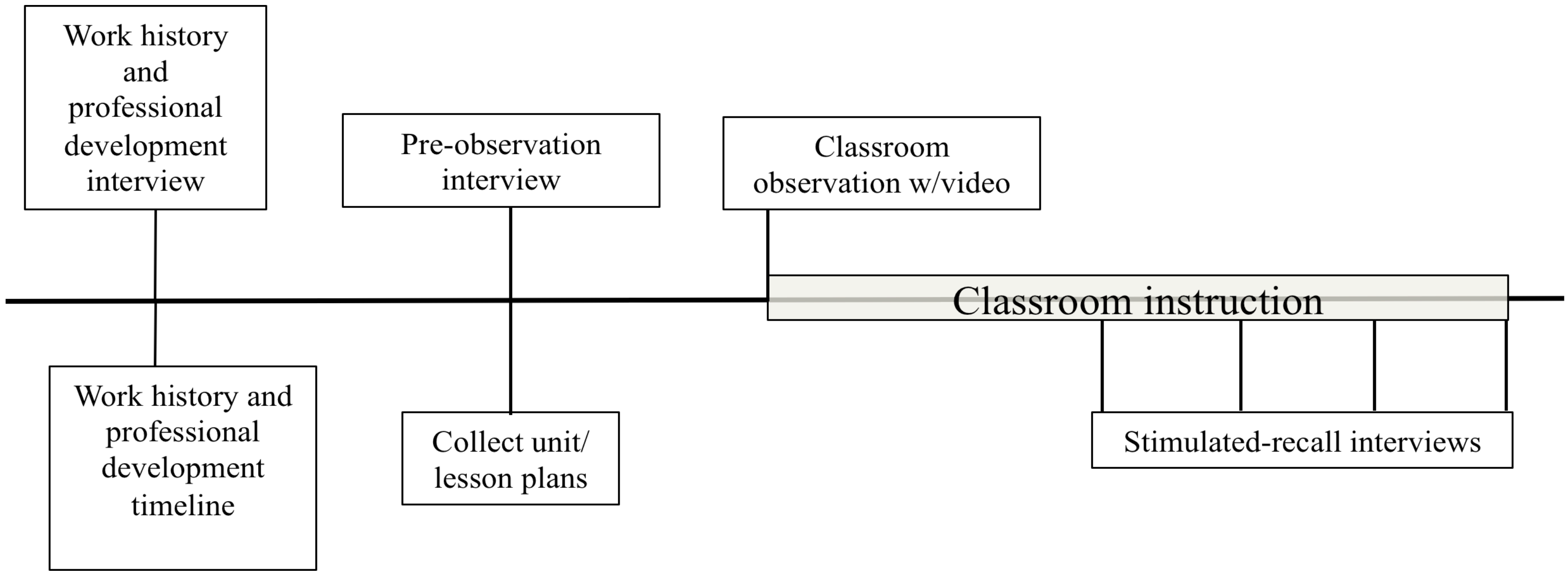

Figure 3. Data collection timeline.

Work History and Professional Development Interview and Timeline

The purpose of the interview and timeline on work history and professional development (PD) history was two-fold. First, the interview was used to obtain information regarding the teacher's work history and PD experiences. Second, the information obtained from the interview and timeline was used to help structure questions and provide more concrete experiences from which the teacher could draw during future stimulated-recall interviews.

The open-ended interview (see Appendix A) was designed to capture the participant's work history and PD history throughout his or her career. For example, I asked questions such as: Where was your first job? What did you teach? What was the school like? What type of professional support did you have at your first job? Are there any supports that really stand out to you as being significant?

During the interview, I generated an annotated timeline that detailed the participant's number of years of teaching, history of teaching the topic, time in the district, PD experiences, previous teaching experience, related experiences that inform the teacher's affinity for teaching the topic or comfort with the topic, etc. I constructed the timeline on a blank sheet of paper while sitting beside the participant during the interview. The purpose of constructing the timeline with the participant was to provide a point of reference from which the participants could elaborate on past experiences and conceptions. The construction of the timeline facilitated conversation and stimulated memories as the teachers recalled their work history, sometimes physically pointing to specific time periods on the timeline while also verbally "filling in" other time periods as they remembered experiences.

The process of generating a timeline of the participant's significant experiences based on their memory and conceptions is consistent with phenomenography. This source of data values the participant's experiences from their perspectives and also helped me to build rapport with the participants prior to classroom observations and subsequent interviews. I treated the work history interview and timeline, however, as a secondary data source because the responses to the interviews and timelines were ultimately used to inform the stimulated-recall interviews with the participants. The interviews and timeline provided information to help address the question of the participants' experiences and their changing knowledge, but they did not comprise as rich a data source when compared to the stimulated-recall interviews. The interview and timeline on work history and professional development was conducted approximately one week before the teachers began teaching the energy unit and lasted about 45 minutes.

Unit/Lesson Plans

Prior to instruction, I asked the participants to provide me with copies of their unit or lesson plans (depending on how the teacher creates plans), detailing what would happen at the beginning, middle, and end of each day or instructional sequence. The purpose of the plans was to provide a general overview of the teacher's instructional plan for the lesson/unit and serve as a source for interview questions regarding the teacher's knowledge about using representations. I asked that the plans include what the teacher and students would be doing at the beginning, middle, and end of the lesson/unit. I asked that they give me these plans no later than the beginning of the pre-observation interview.

The unit/lesson plans served as a secondary source for helping to explore the participants' knowledge of using representations. Specifically, the lesson plans helped to provide an overview of all the representations that the teachers were planning to use and the sequence of those representations. In addition, the lesson plans served as a foundation from which I asked interview questions regarding other aspects of PCK (e.g., assessment) in relation to representations.

Pre-Observation Interview

The pre-observation interview (see Appendix A) served to bring clarification and elaboration to the lesson/unit plans. During the semi-structured interview, the teacher discussed what they had planned and how they intend the instruction to play out. The interview was based on the observation interview protocol developed by the Re-SMAR^{2}T project team (Abell, 2006) and focused on all aspects of the Magnusson model of PCK (Magnusson et al., 1999). Example questions [and PCK component] included: What do you think students will already know about energy [student understanding]? Why did you choose to start with that strategy [instructional strategies]? Where did you get your ideas for teaching energy [curriculum]? How will you find out if students learned what you intended [assessment]? How do you view the students' role in a typical lesson in terms of how they use representations [orientations]?

In addition, I focused the majority of the questions on the ways that the teacher planned to use representations. For example, I asked questions intended to probe the extent that the teachers thought holistically about planning and using representations as well as if the teacher had a sequence of representations in mind or if the teacher even thought in terms of a sequence. Sample questions focused specifically on representations included: How do you think this (picture, graph, equation, etc) helps students learn about energy? Did you consider representing this idea another way? Where did this representation come from?

The pre-observation interview helped to focus the classroom observations and to stimulate questions for future stimulated-recall interviews. The pre-observation interview occurred approximately one week prior to the start of instruction.

The pre-observation interview served as a primary data source for investigating the participants' knowledge of using representations for teaching, as the interview provided rich data in relation to the teacher's knowledge of teaching. From the standpoint of phenomenography, the pre-observation interview provided a shared experience and a common understanding from which we could have conversations about the participants' experiences.

Classroom Observation with Video

Classroom observation is consistent with the underpinnings of phenomenography as it provides a foundation for building commonality from which the researcher and participant can talk about the participant's experiences. For this study, the classroom observations and video recording occurred each day that the teacher taught the topic, starting on the first day of instruction and concluding with the final day of instruction (Allie, Findlay, and Jake took 16, 14, and 10 days respectively to complete the unit). I took field notes during the observation of all instances and uses of external representations and noted when the instances occurred relative to the timer on the videotape so that they could be revisited during the stimulated-recall interviews (Pirie, 1996; Schempp, 1995). The purpose of the video was to help the teacher recall and comment on specific instances that I observed. I observed the instruction from the back of the classroom. The videos were only used to provide a record of instruction and for the purpose of supporting stimulated-recall interview questions. The videos were not transcribed or analyzed as a source of data. I also collected any handouts, worksheets, readings, quizzes, or tests that the students received during the time that I was observing. These artifacts were also used to support the stimulated-recall interviews.

Stimulated-Recall Interviews

The purpose of the stimulated-recall interviews (Pirie, 1996; Schempp, 1995) was to probe the teacher's knowledge, beliefs, and purposes regarding their use of representations during instruction. In addition, the interview questions (see Appendix A) helped probe the ways that the teacher used specific representations in the past and the experiences that promoted change in the use of representations for teaching this topic. The interviews were semi-structured (Patton, 2002) and adapted from the Re-SMAR^{2}T interview protocol (Abell, 2006). The interview questions were focused on selected video clips and classroom instances identified during the observation and informed by the teacher's lesson plans, responses on the work/PD interview, and pre-observation interview. Example questions include:

- Tell me about that representation (graph, chart, diagram, etc). Why did you decide to use that? Have you always used that? When did you first start using it in that way? Why did you start using it that way? What experiences informed the way you use it now?

- I remember from one of our earlier interviews and from your timeline that you had a professional development experience (workshop, seminar, class, etc) on this topic. Did that experience influence the way you decided to use representations today? How? What was it about the PD experience that prompted you to change this way?

- How did this representation help you achieve your overall goals? How does the way you used it reflect your understanding of how students learn?

> Do you remember any experiences that caused you to think about using representations in this way? Tell me about that experience? What made it so impactful?

The stimulated-recall interviews occurred four times over the course of the unit every three to four days. The interviews were conducted at the end of the class or at the end of school day; whichever was easiest for the participant. The stimulated-recall interviews served as the primary data source for this study.

Data Analysis

As described above, a phenomenographic analysis aims for description, analysis, and understanding of variation in people's experiences regarding some phenomenon (Marton, 1981). In this study, the phenomenon is *the development of knowledge for using representations to teach the topics of energy transformation and transfer*. Consequently, the focus of the analysis was on describing *the total variation in veteran teachers' experiences* in developing this knowledge. However, exploring variation in the experiences of developing knowledge necessitated an analysis of two distinct categories: 1) teacher knowledge and 2) variation in experiences.

Although these two categories are distinct, the analysis of both categories was governed by the philosophical and methodological assumptions undergirding phenomenography. For example, a phenomenographic analysis results in the articulation of the participants' various experiences in the form of distinct categories of description, or, an outcome space. This outcome space is based on the collective analysis of the individuals' conceptions of their experiences. Consequently, the outcome space does not reflect the entirety of any one participant's conceptions, but instead the various experiences of all three participants viewed collectively. Because of this, the overarching pattern for the analysis was to begin with the participants' individual accounts and descriptions and to build towards more generalized descriptions of the participants' knowledge and experiences as a group (versus beginning with the individual descriptions and contrasting, critiquing, and/or comparing the individual differences). However, the analysis of teacher knowledge differed from the analysis of variation in experience because the intended outcome of each analysis was different.

The overarching purpose of the analysis of the participants' experiences was to develop an outcome space that captured the variation in their experiences of developing specialized knowledge. However, the overarching purpose of the analysis of teacher knowledge was not to describe the participants' experiences, but to describe their knowledge. Consequently, the result of the analysis of the participants' knowledge was a description of their knowledge in the form of assertions, whereas the end result of the analysis of the variation in the participants' experiences took the form of an outcome space. A description of the two different analyses follows.

Teacher Knowledge

The analysis of teacher knowledge was divided into three phases: 1) identification of central representations, 2) lesson summaries and participant PCK, and 3) historical use of representations. The purpose of identifying central representations was to narrow the field of representations used by the participants down to a few representations that as a group were able to capture and reflect the scope of the participants' knowledge for using representations. This knowledge was then flushed out in the lesson summaries and participant PCK phase. Finally, identifying how representations were used historically allowed for a description of the change in the participants' knowledge for using representations. The three phases of the analysis are described below.

Identification of central representations. For the initial phase in the analysis of teacher knowledge, I started by generating a list of all the representations that were used by the individual teachers. This list was compiled by reviewing the lesson plans and observation notes for all instances where representations were used during instruction. Second, each of the different representations was assigned a coding folder (e.g., "Pie Charts") using Nvivo 8 (a qualitative analysis software). I then coded each transcript for representations by selecting every reference in the transcript to a specific representation and assigning it to its appropriate coding folder. For example, a statement by Jake where he explained that, "We get into things like today, when I took the pie charts and I said alright, if I divide a pie into four equal parts, then you get four pieces of pie" was assigned to the "Pie Charts" coding folder.

Third, I used Nvivo 8 to run a frequency analysis of all the coding folders to determine which of the representations appeared most often throughout all of the interviews. The frequency analysis resulted in a hierarchical list of all references in each coding folder, from greatest frequency to smallest frequency. For example, representations that were only discussed a few times, or briefly, ended up at the bottom of this list (e.g., Ball-and-Stick Model) while representations that were referred to multiple times, or in great length, ended up at the top of the list (e.g., Pie Charts). I used this analysis to identify the more central representations used by the teachers in the energy unit as evidenced by their reoccurring nature throughout the interviews.

Fourth, I looked for support for the representations identified as being more central (in the frequency analysis) by examining each teacher's goals for the unit (as identified in their lesson plans, pre-observation interviews, and the district Essentials) and by looking over the final exams and corresponding interviews. A comparison of the teachers' goals and assessments with the frequency analysis resulted in the identification of three representations that were central to the participants' teaching of the energy unit. As a group, the central representations were able to capture and reflect the scope of the participants' knowledge for using representations to teach the energy unit.

Lesson summaries and participant PCK. In the next phase of the analysis, I generated summaries of each participant's instruction throughout the unit using the notes that I took during my observations and by watching sections of the video recordings of each teacher's instruction. I divided the summaries into three sections corresponding to the three representations identified as central to the participant's instruction in the energy unit, as all three participants introduced the central representations in the same order. The summaries were focused on the participants' instruction leading up to and introducing each central representation.

Second, I re-read each transcript and pulled out all instances in the interviews that corresponded to each section of description in the summary of the participant's instruction. For example, a section of the summary of Findlay's instruction leading up to the introduction of pie charts states, "The lecture concluded with a brick pendulum demo…for their homework, the students were supposed to explain why the student did not get hit in the face with the brick." Therefore, from the stimulated-recall interview, I pulled out the instance in the interview that corresponded to this section of her instruction where Findlay explained that the homework assignment was "just something for them to walk out the door and have to struggle with a little bit so that when we come in and then I introduce pie charts…they're able to make the connections and string it together." I followed this pattern of re-reading each transcript and pulling out all instances in the interviews that corresponded to each unit summary for all three participants. This analysis resulted in a document containing every instance from the interviews that corresponded to the summaries of instruction.

Third, I coded all instances from the interviews (that corresponded to the summaries of instruction) for all five components of PCK by reading each instance and assigning it to one or more component of PCK. The component descriptions were informed primarily by the five component characteristics as described by Magnusson et al. (1999), Friedrichsen, van Driel, and Abell (2010), and the work conducted by the Re-SMAR^{2}T project (Abell, 2006). The synthesis of these sources resulted in the following descriptions of the components that served as the coding criteria for the interviews:

- *Orientations*: A participant's general way of viewing or conceptualizing science teaching and learning, including the participant's knowledge and beliefs about the purposes for teaching science at a particular grade level, knowledge and beliefs about the students' role in learning science, knowledge and beliefs about the role of the teacher, and/or knowledge and beliefs about student learning in science.

- *Knowledge of curriculum*: A participant's knowledge of the mandated goals and objectives and/or knowledge of specific curricular programs and materials, including knowledge of the longitudinal curriculum (i.e., the curriculum for the entire unit and/or other units in the course), knowledge of the relationship between ideas investigated throughout the unit, knowledge of curricular resources (e.g. worksheets, lab activities), and knowledge of adapting or modifying curricular materials.

- *Knowledge of instructional strategies*: A participant's knowledge of general approaches to or overall schemes for enacting science instruction and their knowledge of specific strategies that are useful for helping students comprehend specific science concepts. Knowledge of instructional strategies includes knowledge of using specific strategies in specific ways and for specific reasons, knowledge of alternative representations, knowledge of sequencing instructional strategies, knowledge of using strategies to facilitate student learning, knowledge of the purposes for using certain instructional strategies, and knowledge of the multiple uses of individual instructional strategies.

- *Knowledge of student understanding*: The knowledge a participant has about students in order to help the students develop specific scientific knowledge and understanding, including knowledge of the requirements for learning specific science concepts and knowledge of the areas of science that students find difficult. Knowledge of student understanding also includes knowledge of student misconceptions and confusion, knowledge of students' prior knowledge and experiences, knowledge of students' ability and developmental levels, knowledge of students' learning styles, and knowledge of students' preferences, interests, and motivators.

- *Knowledge of assessment*: A participant's knowledge of the approaches that might be employed to assess the specific aspects of student learning that are important to a particular unit of study, including knowledge of assessment strategies, knowledge of when to assess certain ideas, knowledge why to assess at certain points, knowledge of the benefit of using specific assessments, and knowledge of how assessment informs instructional decisions.

The characteristics associated with each component of PCK are captured in grater detail in Table 2.

Table 2

PCK Component Descriptions and Characteristics, Based on Magnusson et al. (1999), Friedrichsen et al. (2010) and Abell et al. (2006).

PCK Component	**Component Characteristics**
Orientations	• Knowledge and beliefs about the goals/purposes of science teaching (e.g., learning to do science, learning about science, etc) • Knowledge and beliefs about the nature of science (e.g., creativity, tentativeness, etc) • Knowledge and beliefs about science teaching and learning (e.g., role of teacher, role of learner, how students learn, etc)
Curriculum	• Reason for use is linked to goals, objectives, purposes, etc • Longitudinal physics curriculum • Vertical science curriculum • Programs for teaching topic • Materials/resources for teaching topic • Activities within curriculum

	• Materials within curriculum • Modification of existing curriculum materials/activities • Reason for use is tied to what is coming up next regarding the *content* (what will be taught) of the unit or subject or skills needed • Use of representation connected to other representations/strategies (e.g., homework examples) coming up • *That* the rep is used for curriculum reasons like goals (versus *how* the rep is used)
Instructional Strategies	• Physics-specific strategies • Energy-specific strategies • Approaches consistent with orientation (use one strategy to engage, another to explain, etc) • Instructional sequence • Creating cognitive conflict • Exploring patterns • Scaffolding • Strengths/weakness of representations • Invented representations • Usefulness of representation to student learning • Activities to help students comprehend concepts or relationships • Reason for use tied to what is coming up next regarding how using one representation somehow informs the learning of another representation • *How* the representation was used • Comparison of representations to other representations/strategies • Explanation of how the representation meets the goals, objectives, etc (not just that it is used because it does) • Discussion of the details of the representation • Statements that describe the representation itself as a tool
Student Understanding	• Prerequisite knowledge • Variations in approaches to learning • Knowledge development/development of scientific understanding • Abilities and skills needed • Developmental level • Learning styles • Ability to understand particular representations • Concepts that are difficult to learn • Reason why learning particular concept is difficult • Aspects of topic/concept that are difficult to learn • Common errors • Knowledge needed to comprehend novel problems • Difficulties with science abilities (e.g. problem solving) • Misconceptions • Interpreting student actions and ideas
Assessment	• Aspects of student learning that are important to assess • Methods of assessing specific aspects of student learning • Type (e.g. teacher-constructed) • When (in lesson/unit) to assess • Instrument for assessment • Strategies/procedures for assessment • Activities for assessment • Advantages/disadvantages of particular assessments • Representation/strategy used to find out something about what students know

As an example of coding statements in the interviews to components of PCK, when talking about simple equations as part of bar charts, Jake states that, “The kids are going to be seeing a lot more of these different mathematical expressions and formulas coming up.” In this instance, Jake is considering the longitudinal (or long-term) physics curriculum, so this statement was coded as “Knowledge of Curriculum.” But in another instance, referring to the same simple equations, Jake states that the equations, “Can help me reiterate the Law of Conservation of Energy, especially to the lower level kids. I think this helps more with the lower level kids than the upper level kids because I don’t think the upper level kids have any problem with this anyway.” In this instance, Jake refers to the equations as helping him meet the unit goals regarding the Law of Conservation of Energy, but also that he uses the equations to help specific students and that some students do not need the extra help. Therefore, this statement was coded as “Knowledge of Curriculum” due to the connection to the unit goals, “Knowledge of Instructional Strategies” because he distinguishes how the representation is useful for meeting the needs of particular students, and “Knowledge of Student Understanding” because he recognizes that some students have difficulties with the content while others do not. This process of coding statements in the interviews for the five components of PCK was carried out for all three participants for all the sections of the interviews that corresponded to the lesson summaries.

Fourth, I grouped each statement by its participant, by its central representation, and by its PCK component. For instance, every statement that Allie made about pie charts (a central representation) that was coded as Knowledge of Instructional Strategies was grouped together. Similarly, every statement that Allie made about pie charts that was coded as Knowledge of Curriculum was grouped together. This resulted in a collection of documents that contained every statement made by each participant about each central representation, organized around the five components of PCK, for a total of nine separate documents (three participants discussing three different central representations).

Fifth, I generated summary sentences of each statement for each PCK component for each participant. For example, talking about the instructional strategy of using a pendulum demonstration as an introduction to pie charts, Findlay states, “It’s more for the drama and the memory of them seeing that…I want to be able to refer to it and they remember it. And so I think that that’s what I’m trying to make – memorable moments.” In this statement, the main ideas are that the pendulum demonstration creates an element of drama and that it is memorable to students. Consequently, I summarized the statement using the following sentence: Pendulum demo provides drama and is memorable. It is important to note that I kept the summary statements as close to the participants’ descriptions as possible, versus summarizing each statement in light of science education theory. For example, Findlay’s description could have been summarized as “engage students before explaining to students,” a statement that reflects a theoretical perspective regarding how students learn science. However, because phenomenography takes a second-order perspective from which descriptions of reality stem directly from the accounts and conceptions of the participant regarding the ways in which he or she experienced the phenomenon (versus the researcher making a statement about the participant’s account), I focused creating summary statements that reflected the participants’ language and conceptions.

As another example, referring to introducing pie charts incrementally, Findlay states, “My thinking is to break it down into baby steps, let them feel successful, let them feel confident, let them walk out the door feeling physics is something that I can do.” This statement reveals an element of Findlay’s orientation regarding her belief about the teacher’s role in the classroom. I summarized her statement using the following sentence: Break ideas down so students feel that physics is something they can do. The process of summarizing each statement resulted in a list of sentences for each component of PCK that taken together provided a basis from which to describe and summarize the participant’s knowledge regarding each central representation.

It is important to note (as mentioned above), that many of the statements in the transcripts could be coded (and were coded) as reflecting multiple components of PCK. For example, in the example above, Findlay described her use of a pendulum demonstration, stating, “It’s more for the drama and the memory of them seeing that…I want to be able to refer to it and they remember it. And so I think that that’s what I’m trying to make – memorable moments.” As described above, this statement could be coded as knowledge of instructional strategies because refers to a specific reason for using a specific strategy. However, this statement also reflects Findlay’s knowledge of student understanding in terms of student learning styles and interests. Consequently, for the purposes of creating summary statements about the participants’ knowledge in the specific components of PCK, I could have used this example for knowledge of instructional strategies or knowledge of student understanding. Ultimately, I selected examples for specific PCK components that I felt accurately reflected the participant’s knowledge in the specific component based on my observation and the entire set of transcripts.

Finally, I generated assertions about the participants' knowledge based on a comparison of the individual summaries. Consistent with phenomenography, the assertions reflected a collective analysis of the individual participants' knowledge, but did not seek to describe the differences, provide critiques, or make comparisons between the participants.

Historical approach to energy instruction. The purpose of the final phase of the analysis of teacher knowledge was to identify how each participant historically used representations so that comparisons could be made between the current knowledge that they have regarding representations and their previous knowledge. The primary source of data for this analysis was the participants' recollections and self-reports of their previous experiences. And although these conceptions have different evidential status when compared to the participants' reflections on their current practice, through the lens of phenomenography, the participants' recollections of their previous experiences reflect their present reality concerning their previous experiences and can serve as a source from which to make comparisons to their current instruction.

I began this phase of the analysis by re-reading each transcript and identifying all of the instances in the interviews where the participants described how they historically used or thought about representations. I then compiled all of these instances and generated summaries for each participant. The summaries included descriptions of both how they previously taught the topics of energy transformation and transfer as well as what they knew about representations for teaching energy. Using the summaries, I compared the participants' current instruction with their previous instruction and generated a list of the differences. I then categorized the items on the list of the differences by their corresponding knowledge component in the PCK model (although these items did not necessarily represent PCK). For example, Jake described that when he first started teaching, he was unaware of student misconceptions about energy. Therefore, this item was classified under the PCK component "Knowledge of Student Understanding" (although this item actually described Jake's limited knowledge of student understanding). I made similar classifications regarding the participants' previous knowledge (or lack thereof) for teaching energy for all of the items on the list. Next, I compared the items describing the participants' previous knowledge for using representations to the knowledge described in the analysis of their current instruction and generated descriptions of the participants' change in knowledge organized around the five components of PCK. Like the assertions regarding the participants' current knowledge, the descriptions of the participants' change in knowledge were consistent with a phenomenographic analysis and reflected a collective analysis of the individual participants' change in knowledge, but did not seek to describe the differences, provide critiques, or make comparisons between the participants. These descriptions served as the basis for assertions regarding the change in the participants' knowledge.

Variation in Experiences

The analysis of variation in experiences was divided into three phases: 1) identification and categorization of the experiences and sources corresponding to the participants' instruction focused on the central representations, 2) identification of the experiences and sources corresponding to the instruction for the entire energy unit, and 3) descriptions of the experiences and sources corresponding to the participants' instruction for the entire energy unit.

The purpose of identifying and categorizing the experiences and sources corresponding to the participants' instruction focused on the central representations was to generate a list, or outcome space, that captured all of the variation in the participants' experiences that contributed to the development of their knowledge for using the central representations to teach energy. Indentifying the experiences and sources corresponding to the participants' instruction for the entire energy unit provided additional support for the experiences and sources included in the outcome space as well as an indication of the relative significance or dominance of specific experiences on the development of the participants' knowledge. Finally, describing the details of the experiences highlighted the features of the experiences that contributed to their impact on the participants' knowledge for using representations to teach the topics of energy transformation and transfer.

Experiences corresponding to the central representations. For the analysis of the experiences and sources corresponding to the participants' instruction focused on the central representations, I revisited the lesson summaries and corresponding sections of the interview transcripts that were generated for the analysis of teacher knowledge as described previously. Whereas in the analysis of the participants' knowledge I focused on the participants' descriptions and explanations of their instruction regarding the three central representations, for this analysis, I revisited the same sections of the transcripts but focused instead on the participants' descriptions and explanations about the experiences and sources that informed their knowledge. For example, discussing her instruction, Findlay explained, “One of the things I do is I give them these ABC letters.” In the previous analysis of the participants’ knowledge, I focused on Findlay’s knowledge of the ABC letters for teaching energy. However, for this part of the analysis, I focused on the next section of the transcript where Findlay explained that she “got them from Physics First.” In this case, Physics First was identified as the source of Findlay’s knowledge for using the ABC letters to teach energy concepts. I followed this pattern of revisiting each transcript and pulling out all instances in the interviews that corresponded to the experiences and sources informing the participants’ knowledge for using the central representations. This analysis resulted in a list of experiences and sources that captured the instances in the interviews where the participants described the experiences and sources informing their knowledge for using the central representations to teach the topic of energy transformation and transfer. This list represented the phenomenographic outcome space and was based on a collective analysis of individual experiences and revealed something distinct about the ways that the veteran teachers experienced the process of developing knowledge for using representations. Constructed through the lens of phenomenography (Marton, 1981, 1986, 1994; Patton, 2002; Richardson, 1999; Uljens, 1996), the categories: 1) were in clear relation to the phenomenon, 2) revealed something distinct about a particular way of experiencing the phenomenon, 3) were connected in a logical way to each other, and 4) were as few in number as feasible and reasonable for describing the critical variation.

Experiences corresponding to representations in the entire energy unit. The purpose of indentifying the experiences and sources corresponding to the participants’ instruction for the entire energy unit was to provided additional support for the experiences and sources included in the outcome space as well to provide an indication of the relative significance or prominence of specific experiences on the development of the participants' knowledge. Whereas the first phase of the analysis only focused on the sections of the transcript where the participants discussed their instruction regarding the central representations, this phase of the analysis focused on the entire set of transcripts (including the central representations) during which the participants were asked about every representation that they used throughout the entire energy unit. This phase of the analysis helped to paint a more complete picture of the sources and experiences informing the participants knowledge for using representations to teach energy.

For this phase of the analysis, I revisited each of the transcripts and identified all of the experiences and sources that informed the participants' instruction and knowledge for using representations for the entire energy unit. I conducted the analysis by examining each interview for: 1) every description of an experience or source and 2) the strategy, representation, or knowledge component informed by the experience. For example, Jake explained, "The first time I [taught the energy unit], man, you take a look at the test that I gave, they were bombing similar questions...and then the next year that I gave it, you start to break it down a little bit more and make adjustments and it becomes easier. And of course the third or fourth year that you finally get through to it, you started to figure out oh, if I do this right now, it makes it really easy for the kids to understand." In this statement, the strategy was identified as "breaking down ideas" and "teaching experience" was identified as the experience. In some cases, multiple experiences and sources informed a single strategy or knowledge component. I followed this pattern of identifying strategies and experiences for each transcript for all three participants.

Second, I re-read the list of sources and looked for broader classifications or categories that captured all of the sources. For example, sources such as coaching sports, training dogs, and having teenage children were all categorized as “Non-academic Life Experiences.” I followed this pattern of generating broader categories based on the list of sources for all of the sources on the list.

Third, I took the list of broader categories and compiled all of the strategies, representations, and knowledge components informed by the source. This analysis resulted in a frequency distribution regarding the number of strategies, representations, and knowledge components informed by each of the experiences or sources. For example, the source “Physics First” informed twenty different representations, including pie charts and bar charts, while “Non-academic Life Experiences” only informed the participants’ knowledge for the three areas of introducing the system circle, learning by association, and examples. This analysis and the corresponding frequency distribution resulted in the identification of the sources that played a more prominent role in shaping the participants’ knowledge and the sources that contributed less to shaping the participants’ knowledge (as indicated by their relative frequencies).

Finally, I compared the sources identified in this phase of the analysis to the outcome space generated in the first phase of the analysis and looked for support for the experiences and sources included in the outcome space, as well as an indication of the relative significance or prominence of the experiences identified in the outcome space based on their relative frequencies.

Descriptions of the experiences and sources corresponding to the participants' instruction for the entire energy unit. For the last phase of the analysis, I explored the details of the experiences and sources identified in the outcome space. The purpose of this phase of the analysis was to characterize the nature of the participants' experiences by identifying every reference to each experience in the outcome space made by all three participants throughout the entire interview process. Compiling all of the participants' descriptions of their experiences allowed me to paint a more complete picture of the characteristics of the experiences that informed the participants' knowledge. In order to avoid unnecessary repetition, and because the emphasis of this phase of the analysis was on capturing the characteristics of the experiences (versus the connections between the experiences and specific components of PCK), I did not re-emphasize the connections between the experiences and the specific knowledge components informed by the experiences. Instead, I only focused on the connections between a specific experience and any characterization of that experience. Specific support for the connections between the experiences and the specific components of PCK was provided as a result of the preceding analyses. It is important to note, however, that in some cases, the sections of the transcripts informing this phase of the analysis were the same as the sections of the transcript informing the previous analysis. The reason for this is that the focus of this phase was on describing the characteristics of the experiences, whereas the focus of the previous analysis was on identifying the link between the experience and the representation.

I conducted this phase of the analysis by revisiting each description of the experiences and sources as described by each participant throughout the entire interview process (versus just the central representations). Using the participants' descriptions, I identified the characteristics and features of the experiences and sources. For example, describing his experiences with Physics First, Jake explained, "It's not just that Physics First that makes you do it [use multiple representations], I think it's once you see it happening and how it works, then you start to do it on your own for everything that you teach." In this statement, Jake described two of the components of Physics First that informed his knowledge of using multiple representations, specifically, 1) participating in building representations and 2) observing strategies and how they work. These two components were therefore identified as characteristics of Physics First.

I repeated this process for every instance in the interview transcripts where the participants described the characteristics and features of the experiences and sources identified in the outcome space. Based on the analysis, I generated a table compiling the characteristics of the experiences and sources as described by the participants. This table then served as the source from which to describe and discuss the characteristics and features of each of the experiences and sources identified in the outcome space.

Role of Researcher and Limitations

As I described at the beginning of the methods section, qualitative approaches to research must acknowledge and account for varying levels of interaction between participant and researcher. These interactions contributed to and informed both the data collection and data analysis portions of the study.

In terms of data collection, it has been suggested that "the knowledge that people use to regulate and make sense of social actions remains at the level of 'practical consciousness,' in that it is tacit or implicit knowledge that cannot be readily articulated in discourse" (Richardson, 1999, p. 59). Therefore, it was essential that I ask questions during the interview in such a way that facilitated and promoted the process of making tacit knowledge explicit. To this end, I developed the interview protocols so that they would help facilitate the task of probing the participants' knowledge. This was done by including multiple prompts designed to probe the participants' knowledge and experiences from multiple angles. In addition, the interview protocols were designed to be similar to the ReSMAR^{2}T (Abell, 2006) interview protocols with which I had two years experience using to probe for tacit teacher knowledge. Despite these approaches, the participants were still unable to recall all of the experiences informing the development of their knowledge for using certain representations.

Second, in terms of data collection, I have learned from my experiences interviewing for the ReSMAR^{2}T (Abell, 2006) project that it is possible to ask interview questions in such a way so as to lead participants to the answers that I want to hear. This is problematic, as the goal of phenomenographic research is on describing the participants' conceptions, regardless of how they fit into my conceptions of teaching and learning. In order to help avoid this, I designed the interview protocol questions so as to elicit the participants' conceptions and included reminders throughout the protocol that the focus of the interview was on the participant's conceptions. Furthermore, any instances in the transcripts where I recognized this happening, I either omitted those portions or qualified them before using them in the analysis.

Finally, one critique of phenomenography is the problem of trying "to describe the world as people experience it" (Marton, 1978, p. 2) using data collection methods that are limited in their ability to actually observe people's experiences (Richardson, 1999).

This critique is understandable, but was addressed by carefully designing and conducting the interviews. In addition, this critique is based upon an ontological assumption contrary to phenomenography's, specifically, the phenomenographic assumption that experience is inextricably linked to reality, and that reality is considered to exist through the way in which a person perceives himself or herself to be related to the world. In this sense, perception provides a direct link to experience. Nevertheless, the findings must be considered in light of the nature of the collected data (i.e., interviews based in part on the participants' recollection of experiences versus interviews of experiences occurring in "real time").

CHAPTER FOUR: FINDINGS

Teacher Knowledge

Identifying Central Representations

The initial analysis of all the representations that were used by the individual teachers revealed that as a group, the teachers used a total of 33 different representations throughout the energy unit. Of the 33 different representations used by the teachers, sixteen were common to all three teachers, specifically: stations objects (e.g. windup toy), T-chart/vocabulary, real-life examples, analogies, demonstrations, system circle, identifying states in writing, pictures on handouts, scenarios, motion marks, pie charts, energy words, energy symbols, photos, bar graphs, and energy work arrows.

Of the 33 total representations used by the participants, the Nvivo frequency analysis revealed that graphics, hierarchy concept map, and ball-and-stick model appeared least often throughout the interviews while pie charts, bar charts, and T-chart/vocabulary appeared most often. A comparison of the representations that appeared most often to the list of representations shared between all three teachers revealed that the three representations that appeared most often in the interviews were also shared by all three participants, supporting the assumption that they played a central role in the teachers' instruction. This assumption was explored further through an analysis of the teachers' goals for the unit and their final assessments.

The analysis of the teachers' goals for the unit (as articulated in the lesson plans and corresponding interviews) and their final assessments (as articulated on the final exams and corresponding interviews) revealed that the three representations identified as being dominant in the interviews from the Nvivo frequency analysis were in fact representations that were central to the participants' teaching of the energy unit. For example, in describing how she planned for the energy unit, Allie explained that she began with the "Essentials." When probed as to what these Essentials were and how she determined them, she explained that the 9th grade physics teachers in the district met as a group to consider, "What are the essential things? What do these kids really have to know?" and that as a result of that meeting they "boiled it down" and came up with four Essentials. Similarly, Findlay and Jake both referred to the district Essentials in describing their goals for the energy unit. At my request, all three teachers provided me with nearly identical copies of the district Essentials, which state that by the end of the energy unit, every 9th grade student should be able to: 1) identify different forms of energy, 2) classify energy as either potential or kinetic, 3) state that energy can be stored or transformed, but never created or destroyed, and 4) describe a physical system in terms of energy storage, transfer, and transformation using various representational tools.

A comparison of the district Essentials with the three dominant representations listed above reveals close alignment between the objectives explained in the district Essentials and the primary concepts described or conveyed by T-charts/vocabulary, pie charts, and bar charts (Table 3).

Table 3

Comparison of Central Representations to District Essential Goals

Representation	Purpose of Representation	Essential Goal Addressed
T-chart/ Vocabulary	Identification, definition, organization, and classification of energy types and forms using words/terminology	1) Identify forms of energy 2) Classify types of energy
Pie Chart	Represent energy of a system, energy transfers and energy transformations within a closed system	3) Law of Conservation 4) Energy storage and transformation
Bar Chart	Represent energy transformations or energy transfers in an open or closed system	3) Law of Conservation 4) Energy storage, transfer, and transformation

Similarly, the final exams that the participants gave their students at the end of the unit reflected the goals in the district Essentials and required student understanding of all three dominant representations. For example, on Jake's final exam, 42% of the total points on the test came from questions that required the students to draw from their understanding of T-charts/vocabulary (e.g., "What is the name for the classification for all energy in motion?"), 13% of the total points required an understanding of pie charts (e.g., "Complete the pie charts below [for a given scenario]") and 45% of the point total required students to have an understanding of bar charts (e.g., "Fill in the bar charts [for a given scenario]"). The final exams given by both Findlay and Allie required similar understandings of the three types of representation.

Taken as a whole, the dominance of T-charts/vocabulary, pie charts, and bar charts in all of the participant interviews along with their alignment with the district Essentials and their importance on the final assessments support the conclusion that they are indeed central representations in all three participant's instruction of energy. Because I have conceptualized PCK as representing specific knowledge for teaching a specific topic, and because these three representations are central to teaching the specific topic of energy, I will discuss the remainder of the findings regarding the participants' knowledge of using representations in terms of these three representations. But first, I will describe the three representations relative to the Physics First curriculum (as written by the curriculum developers).

Physics First curriculum and description of central representations. All of the teachers in the Physics First professional development project participated a total of three summer academies (2006-2008), which focused on instruction and curricular resources designed to prepare the participants for teaching an entire 9th grade physics course. The participants received instruction on the energy unit during their second summer in the project. The training on the energy unit included explicit instruction regarding the recommended goals of the unit as well as activities and other curricular resources (e.g., readings, worksheets, assessments, etc) that corresponded to the goals of the unit. However, although the Physics First project recommended a general sequence of instruction, the participants were encouraged to pick and choose activities and other curricular resources that fit best within their context (e.g., students' needs and abilities, school district goals, classroom setup, etc). Below, I provide a general description of the Physics First energy curriculum (and corresponding representations) as originally written by the Physics First project. Later, in the descriptions of the participants' instruction, it will be evident where the participants did, and did not, adhere to the Physics First curriculum as written.

Physics first energy curriculum. The written Physics First energy curriculum (Kosztin & de la Paz, 2005) began with a description of the big ideas for the unit: 1) for a closed system, energy is conserved and 2) energy can be stored, transferred, or transformed. Based on the big ideas, the written curriculum articulated five learning goals for the students (pp. 5-6):

1. Differentiate between energy transfer, transformation and storage
2. Analyze a physical system in terms of energy storage, transfer and transformation using various representational tools (pictures, verbal descriptions, pie charts, and bar graphs)
3. Relate the concept of work to an energy transfer mechanism
4. Design and conduct an experiment to determine the energy stored in a system
5. Mathematically and graphically determine work, gravitational potential energy, elastic potential energy, kinetic energy, and power

Guided by these goals, the energy unit was divided into a series of instructional activities organized around the 5E learning cycle (Bybee, 1997), which advocates for instruction that begins with engagement in scientific ideas followed by exploration, explanation, elaboration, and evaluation. As written, the curriculum encouraged the participants to engage the students in a series of questions focused on the concepts that would be discussed throughout the unit, followed by an "exploring energy" lab during which the students would investigate the energy associated with various everyday objects (e.g. wind-up toys). The engage/explore phase concluded with a student reading page about the types and forms of energy. For the explanation phase, the curriculum provided an "exploring work" lab, an audio recording (and accompanying worksheet) of an energy lecture by the physicist Richard Feynman (Feynman, 1994), and a series of reading and practice pages focused on the concept of energy conservation and on developing understandings about, and abilities to use, pie charts and bar charts. For the elaboration phase, the curriculum provided a series of lab activities focused on the concepts of work (e.g., mathematical expressions, graphical representations, connections to energy), the types and forms of energy (e.g., mathematical expressions for calculating energy, graphical representations), and power (e.g., measurement, mathematical expressions, connections to work and energy). These lab activities were also supported by a series of student reading pages and practice problems connected to the concepts. Finally, for the assessment phase, the curriculum provided an energy simulation lab.

As described in the previous section, the Westwood school district developed four goals to guide their instruction. However, the four goals developed by the district only reflect the first two goals outlined in the Physics First curriculum, namely, differentiating between energy storage, transfer, and transformation and analyzing a physical system in terms of energy storage, transfer, and transformation using various representational tools. Although it was not explicitly stated in the district Essentials, all three of the participants also discussed the concept of work from a qualitative perspective. Consequently, the district goals, and therefore the participants' instruction, excluded the Physics First goals regarding quantitative mathematical expressions (equations, graphs, etc) connected to the concepts of work and power, and instead, only focused on qualitative representations (e.g., pie charts, bar charts, etc) connected to the concepts of energy conservation, energy transfer, energy transformation, energy storage, and work. The participants explained that if time permitted, they would revisit the energy unit near the end of the school year and discuss the concepts and quantitative representations that they excluded, because by the end of the year, the students' math skills would be more sophisticated. However, for their current instruction, the participants only focused on concepts explained by the qualitative representations. Consequently, the three central qualitative representations used by the participants are described below.

T-charts/vocabulary. The representation T-charts/vocabulary captures all instances in the unit where the focus is on identification, definition, organization, and/or classification of energy types (e.g., kinetic or potential) and/or forms (e.g., thermal, gravitational, etc) using words or terminology. For example, all three participants expected that their students understand the distinction between the description of kinetic energy as the "energy of motion" versus the description of potential energy as "energy that is stored." Similarly, all three participants expected that their students could describe and distinguish between forms of energy, such as gravitational energy as the energy due to an object's vertical position relative to ground-level or thermal energy as the energy associated with an object getting warmer or cooler due to the motion of the molecules that make up the object. Finally, all three participants expected that their students could match the forms of energy to their corresponding type of energy (e.g., gravitational energy is a form of potential energy). For all three participants, the summation of these ideas took the form of a T-chart that organized the forms of energy by their name and type (Figure 4). In the T-chart, the forms of energy are positioned in the column appropriate to their corresponding type of energy.

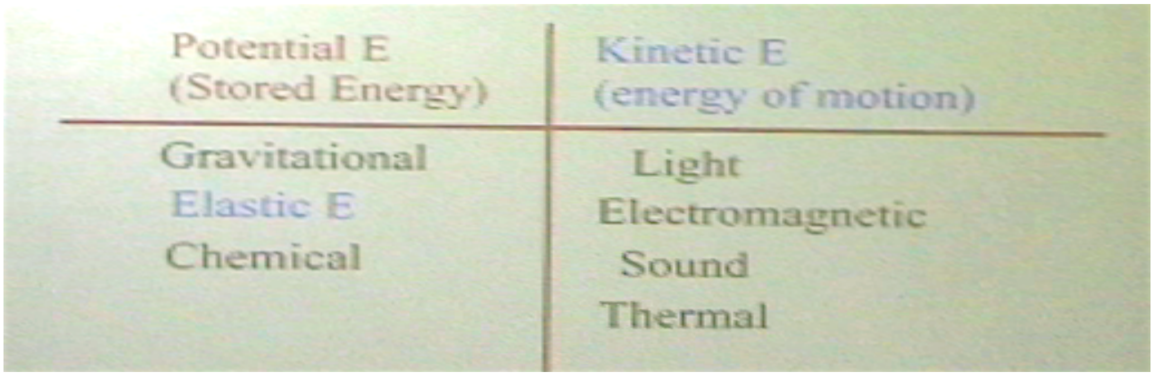

Figure 4. Image of a T-chart as displayed on the SMART Board in Jake's classroom.

Pie charts. Pie charts were used in the unit to represent the energy of a system or the transformation of energy within a closed system. In all instances, pie charts were used to describe graphically the change in energy for a given scenario, and therefore the pie chart representation always consisted of two or more pies to show the change in energy. For example, in the image below from Findlay's classroom (Figure 5), the scenario is that of a ball falling from rest.

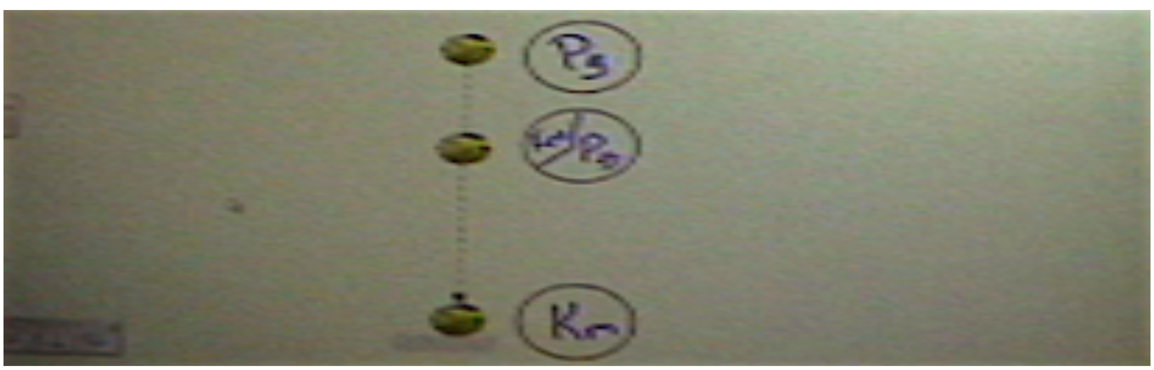

Figure 5. Image of pie charts as displayed on the SMART Board in Findlay's classroom.

The motion of the ball is depicted by a ball drawn at three different positions. A pie chart is drawn next to each position of the ball, showing the type and form of energy and the relative amount of each type and form. In the scenario of the ball falling from rest, the ball has 100% potential gravitational energy at the top position and 100% kinetic mechanical energy at the bottom position. At the middle position, the ball has a larger proportion of potential gravitational energy and a smaller proportion of kinetic mechanical energy. The sizes of the slices of pie represent the differences in the proportions. Because the energy in the pie chart must always add up to 100% (i.e., a full circle), pie charts were only used to represent energy changes in closed systems (i.e., systems where the energy is always 100% and energy cannot be added or taken away).

Bar charts. Bar charts were used to represent the energy of a system, the transfer of energy, or the transformation of energy within closed and open systems. Like the pie chart, bar charts were used to describe graphically the change in energy for a given scenario. Consequently, the bar chart representations always consists of two sections of bars, one section representing the initial state of the system (bars on the left side) and the other representing final state of the system (bars on the right side). In the example below from Allie's class, the two sections of bars are separated by a circle in the middle (Figure 6).

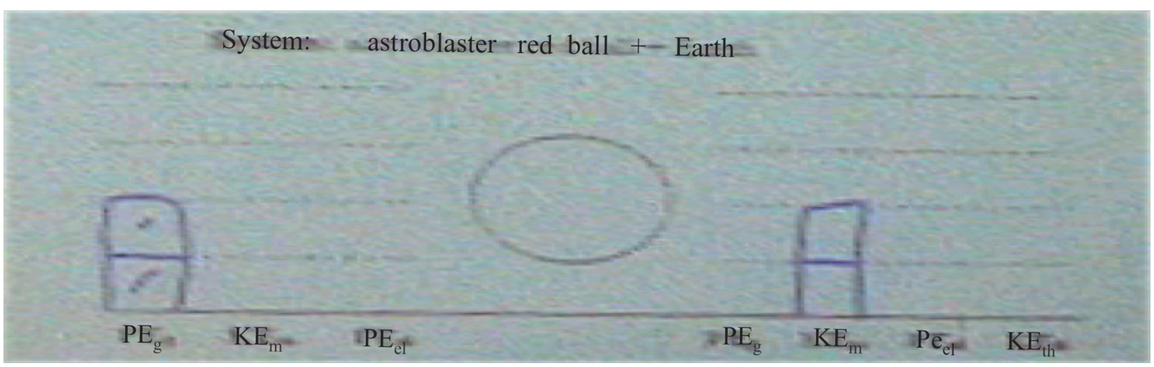

Figure 6. Image of a bar chart as displayed on the SMART Board in Allie's classroom [enhanced].

The circle represents the system in question (this may or may not include all objects in the scenario). In the example above, the scenario describes a small red ball stacked on top of four larger balls (a toy called an Astroblaster) being dropped to the ground, but the system only includes the small ball and the earth (excluding the four larger balls). Below each section of bars are symbols denoting energy types and forms (e.g., PE_g, KE_m). Blocks are then drawn above the symbols corresponding to the relative forms and amounts of energy present in the initial state (e.g., two bars of gravitational potential energy) of the system compared to the final state of the system (e.g., two bars of kinetic mechanical energy). Because the circle in the middle allows for the identification of what is in the system and what is out of the system, closed as well as open systems can be represented by bar charts.

Lesson Summaries and Participant PCK

The remaining findings about teacher knowledge are organized around the participants' instruction leading up to and focusing on the three central representations. I will use the following pattern to describe the findings: 1) summarize the participant's instruction regarding a single representation, 2) identify the participant's knowledge in terms of the specific components of PCK for the specific representation, and 3) summarize the participant's PCK for the specific representation. I will follow this pattern for the entire findings section, describing all three participant's knowledge of T-charts/vocabulary first, all three participant's knowledge of pie charts second, and all three participant's knowledge of bar charts last. I will conclude the section with assertions about the participants' knowledge.

Jake: T-charts/vocabulary

Summary of instruction. Jake's introduction to T-charts/vocabulary began with an exploring energy lab. Jake told the class, "I want you to do some investigation on your own. I want you to answer some questions on your own on what is energy." So the students rotated through lab stations containing various objects (e.g. windup toys, flashlights) that were set up at each desk and answered the following questions in their notebooks regarding each station: Is there energy associated with the object at your station? If so, what is the energy? Is the energy created, or already there? What is energy? After exploring the stations, Jake brought the class back together so that the students could share what they observed. Students did this by describing the object at a particular station and discussing their ideas about the energy in the object. Jake facilitated this conversation by building upon and asking questions about the ideas that the students offered up (e.g., Is electricity energy? Is light energy? Any idea what we call moving energy?). During this discussion, Jake would either go with the terms that the students came up with because they were in alignment with the terms he was looking for (e.g. light energy) or modify the terms that they used so that they were in agreement with the terms that he wanted (e.g. change the word electricity to electrical energy). In some cases, Jake would go with the incorrect terms that the students used but mention that they would talk about the terms later in the unit (e.g. heat energy). During this discussion, Jake would also ask leading questions about the objects to help draw out student ideas (e.g., Would that work if it was made out of metal?). After discussing all of the stations, he wrote the words "energy transformation" on the SMART Board and explained to the class that all of the objects that they explored transform energy in some way. Next, he elaborated on this idea by discussing the energy transformations behind modern appliances and the impact of these appliances on the students' everyday lives. He then used examples from the objects that the students explored at the stations to consider the ideas of initial state and final state by revisiting all of the objects in terms of the energy transformations that they performed. Jake did this mostly by asking questions and encouraging the students to respond to the questions based on their experiences or ideas. Next, Jake asked the students to write down the word energy in their notebooks and he asked the class to throw out the different forms of energy that they discussed while debriefing the lab. Jake then wrote down the words on the SMART Board in the order that the students shared them. Student responses included gravitational, elastic, chemical, kinetic, thermal, sound, electromagnetic, and light. Through discussion and reasoning with the students, Jake made the case that a tennis ball has gravitational energy (based on a student response to what kind of energy it has) and potential energy (because it has the ability to move). From this, he reasoned that they could divide the energy terms written on the board into groups. Next, based on their experiences in middle school, Jake asked the students what the terms kinetic and potential mean. Through a show of hands and students volunteering answers, he wrote down that potential energy is stored energy and that kinetic energy is the energy of motion. He then used the SMART Board to drag the terms with their qualifiers (definitions) into two columns to make a T-chart, asking the students which energy terms go into which column. For each suggestion that a student offered up, he asked the student to justify his or her reasoning and asked the class their thoughts before moving the term to a category. Often, Jake did this by challenging or questioning their reasoning and assumptions. For some suggestions that the students made (e.g., sound is kinetic because it moves through the air) he clarified how the phenomenon works (e.g., sound is like dominoes). The students then wrote down the final T-chart in their notebooks. Jake mentioned that there were more energy forms (e.g. nuclear) but that they were not going to talk about them.

PCK for T-charts/vocabulary. The analysis of Jake's interviews regarding the sequence of instruction summarized above resulted in a description of Jake's knowledge in terms of the five components of PCK.

Knowledge of curriculum. In the beginning of the unit, Jake introduced T-charts/vocabulary by asking the students to explore objects at stations located throughout the room. The objects at the stations were not selected at random, however, but instead were selected with a purpose in mind. Jake explains:

> I'm trying to get the students to come up with new terminology about defining or identifying different types of energy. So the items that I chose were hopefully going to get the students to think about the different types of energy that we will be discussing.

This statement reveals that Jake selected the objects that he did because the specific objects would help students think about the specific types of energy in the unit. This decision reflects Jake's knowledge of curricular goals and the longitudinal (what has happened and will happen) curriculum, specifically, that his reason for selecting the objects is based on his objectives (students coming up with terminology) and his knowledge of the content that is coming up (types of energy).

Later in the sequence of instruction, Jake asked the students to discuss the forms of energy that they encountered in the various lab objects so that he could write them on the board. Because Jake had a specific goal in mind as he was doing this, he did not accept every answer that the students offer up. He explains, "My biggest key was to make sure that I got to gravitational, kinetic, elastic, all those things that are in the pie charts and the bar graphs because those are where the keys were." This statement reflects Jake's knowledge of the curricular goals, specifically, that the forms of energy that he was looking for were essential for other representations later in the unit.

As a final example of Jake's knowledge of curriculum, Jake explained why he opted to use a T-chart instead of some other representation, stating:

> The goal in the end here is for me to be able to get the kids to be able to draw a pie graph and a bar graph…and if you take a look at the initial states on the left side of a bar graph you only have three things: You have gravitational, kinetic, and elastic. And then, if you take a look at the right side, you have those three things plus thermal. So I didn't need to make an elaborate thing when really all it took was something that was fairly simple.

Again, this explanation highlights that Jake selected a basic T-chart representation containing only specific types and forms of energy because of his knowledge of the curricular goals, specifically, what terms will be needed later in the unit and his goals of helping students learn to draw and understand pie charts and bar charts.

These examples, specifically, that objects were selected based on the unit objectives and future content, that the forms of energy that he was looking for were essential for other representations later in the unit, and that energies in the T-chart are only those needed later in the unit highlight Jake's knowledge of curriculum as connected to his use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 7 at the end of this section.

Knowledge of instructional strategies. During the instruction, the students were asked to discuss the forms of energy that were present in each object in the lab stations. In discussing the energies, the students suggested names for the forms of energy before Jake provided the terms. Jake explains:

> They have to come up with the terms themselves first. And then what I'm going to do is I'm going to give it that name. So for example they talk about all the different things that have energy like the crank up flashlight. So the flashlight produces light. And so is light a type of energy? And if they say yes then boom, it goes on the board. So now light becomes a

> type of energy, but it's a type of energy because they got the chance to see it and experience it.

In this statement, Jake articulates his knowledge sequencing instructional strategies, namely, that students have an experience first and then develop names for the terms based on the experience.

As another example of Jake's knowledge of instructional strategies, Jake discussed why he opted to use a T-chart instead of a concept map. He explains, "This was probably the simplest way the kids could understand that really the energies were divided up into two groups, so that's what I went with…the concept map was more elaborate and this is really more simplistic." In this statement, Jake reveals that he chose the T-chart instead of a more elaborate concept map because the T-chart was more simplistic because items could only fall in one of two groups. This example demonstrates that Jake had knowledge of other representations but that he had a specific reason for choosing the representation that he did.

As a final example, revisiting Jake's statement described in the curriculum section regarding the use of the objects at the stations, Jake explains:

> I'm trying to get the students to come up with new terminology about defining or identifying different types of energy. So the items that I chose were hopefully going to get the students to think about the different types of energy that we will be discussing.

From the perspective of instructional strategies, it is clear that Jake selected a specific strategy (lab stations) for a specific reason (so that students come up with specific terms).

These examples, specifically, that students have an experience first and then develop names for the terms based on the experience, that he chose the T-chart instead of a more elaborate concept map because the T-chart was more simplistic, and that the objects in the stations were selected so the students could come up with specific terms highlight Jake's knowledge of instructional strategies as connected to his use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Instructional Strategies" box in Figure 7 at the end of this section.

Knowledge of student understanding. Discussing the exploring energy lab, Jake explains:

> They get to take a look at energy in lots of different forms which just hopefully puts it in the back of their mind that okay, energy can't just be electricity, it just can't be heat, and give them some ideas that okay now energy can be a lot of different things.

This statement reveals that Jake uses the lab because it helps to address student misconceptions, highlighting his knowledge of student understanding, specifically, that students have misconceptions about energy. Additionally, he identifies the specific misconceptions that students typically have (e.g. energy is only electricity).

As another example of his knowledge of student understanding, Jake elaborates on the strategy of requiring students to develop terms and definitions based on their experiences. He explains, "If they have their own definition of it, they have a little bit more of a deeper understanding of really what it is, instead of memorizing a definition." This statement reveals Jake's knowledge of how students develop scientific understandings, specifically, that students have better understandings if they come up with definitions on their own and that memorizing does not promote deep understanding.

In a final example of his knowledge of student understanding, Jake discussed the point in his instruction where he asked the class to provide him with the definitions of kinetic and potential energy based on their previous courses in middle school. Jake explained that he expected that the students would remember the terms kinetic and potential. However, when asked why he then took the time to teach these ideas, he explained, "Do they all remember what it means? That part I'm betting no." This example reveals Jake's understanding of the students' prior knowledge, specifically that the students will know the words kinetic and potential, but not what they mean.

These examples, specifically, that students have specific misconceptions about energy, that students have better understandings if they come up with definitions on their own, that memorizing does not promote deep understanding, and that students will know the words kinetic and potential but not what they mean highlight Jake's knowledge of student understanding as connected to his use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 7 at the end of this section.

Knowledge of assessment. Throughout his instruction (e.g., when asking students to decide if the forms of energy should be classified as potential or kinetic), Jake required his students to provide justification for their ideas and answers. When asked why he did this, he explained:

> I want to know exactly why they chose that as their answer, because a lot of times they'll pick the right answer but they'll pick the wrong reasons. And if you give me an answer but it's for the wrong reasons, you're still wrong if you ask me.

This statement reveals Jake's knowledge of an assessment strategy, specifically, that student justification reveals why they are answering as they are.

As another example of his knowledge of assessment, Jake discussed why he never required the students to provide a definition of energy in this section of the unit. He explained that he would not assess for a definition of energy:

> Until we get to the very end [of the unit] where I feel like the kids have a better understanding of what all energy is about, and then together we'll come up with an idea of okay, in all relative purposes, what is energy.

This statement reveals Jake's knowledge of when to assess certain ideas (e.g. terminology is assessed near the end of the unit), and why to assess the certain ideas at that point (because the students are building understandings of the terminology throughout the unit).

These examples, specifically, that student justification reveals why they are answering as they are and that he chooses not to assess terminology at this point highlight Jake's knowledge of assessment as connected to his use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Assessment" box in Figure 7 at the end of this section.

Orientations. The summary of Jake's instruction highlights the process of the students starting with everyday objects and working towards organizing and building a T-chart of the terms. Responding to why he took this approach, as opposed to introducing the terms at the beginning, Jake explains:

> I'm not one of those people that like to recite definitions. I'd much rather they come up with their own definition as long as the definition they come up with doesn't have any inaccuracies in it. It may not be 100% accurate, but I feel like if they have their own definition of it, they have a little bit more of a deeper understanding of really what it is.

This statement captures an aspect of Jake's orientation regarding the students' role in learning science, specifically, his orientation that students learn by developing their own ideas.

As another example of Jake's orientation, Jake spent a portion of his instruction explaining how the ideas that the students were exploring are connected to everyday experiences and objects (e.g., appliances). When probed as to why he did this, he explained:

> You should really spend a lot of time on why it is that you're teaching what you're doing and how it's relevant…if kids don't see the relevance of it or if they don't see how it was or is important, then a lot of times it is just something that the kids brush under the table. And you're always trying to do everything that you can to make sure that the things that you do are relevant.

This statement highlights another aspect of Jake's orientation regarding the role of the teacher, specifically, that one role of the teacher is to help students see how scientific ideas are relevant.

These examples, specifically, that students learn by developing their own ideas and that the teacher's role is to help students see how scientific ideas are relevant to them highlight Jake's orientation as connected to his use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Orientations" box in Figure 7.

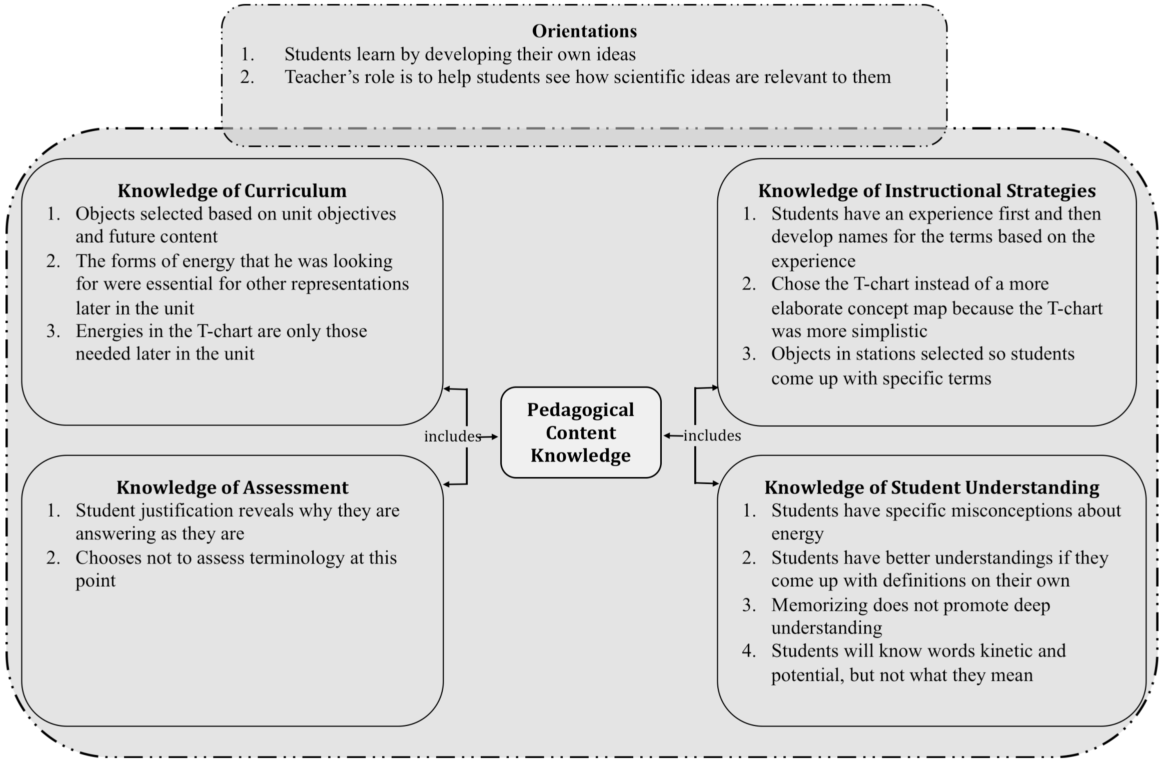

Figure 7. Examples of Jake's knowledge in all five components of PCK for T-charts/vocabulary.

Summary of PCK for T-charts/vocabulary. Viewed collectively, the five components reveal the interconnected nature of Jake's knowledge for using T-charts/vocabulary as a representation for teaching energy. For example, as captured in Figure 8, one aspect of Jake's orientation is his belief that students learn by developing their own ideas. This orientation is reflected in the instructional strategy he uses of having the students come up with their own terms and organizing the T-chart based on having an exploration experience prior to any explanation. But the instructional strategy is also connected to his knowledge of student understanding, specifically that coming up with their own terms helps students confront misconceptions and develop deeper understandings of the concepts. This instructional strategy is likewise connected to his orientation of students developing their own ideas. He also uses the approach of having students build understanding as a way to assess student understanding, specifically by having them justify the ideas that they come up with. And all of this is connected to his overarching goals and objectives for the unit that students will ultimately develop understandings of specific types and forms of energy that they will need later in the unit.

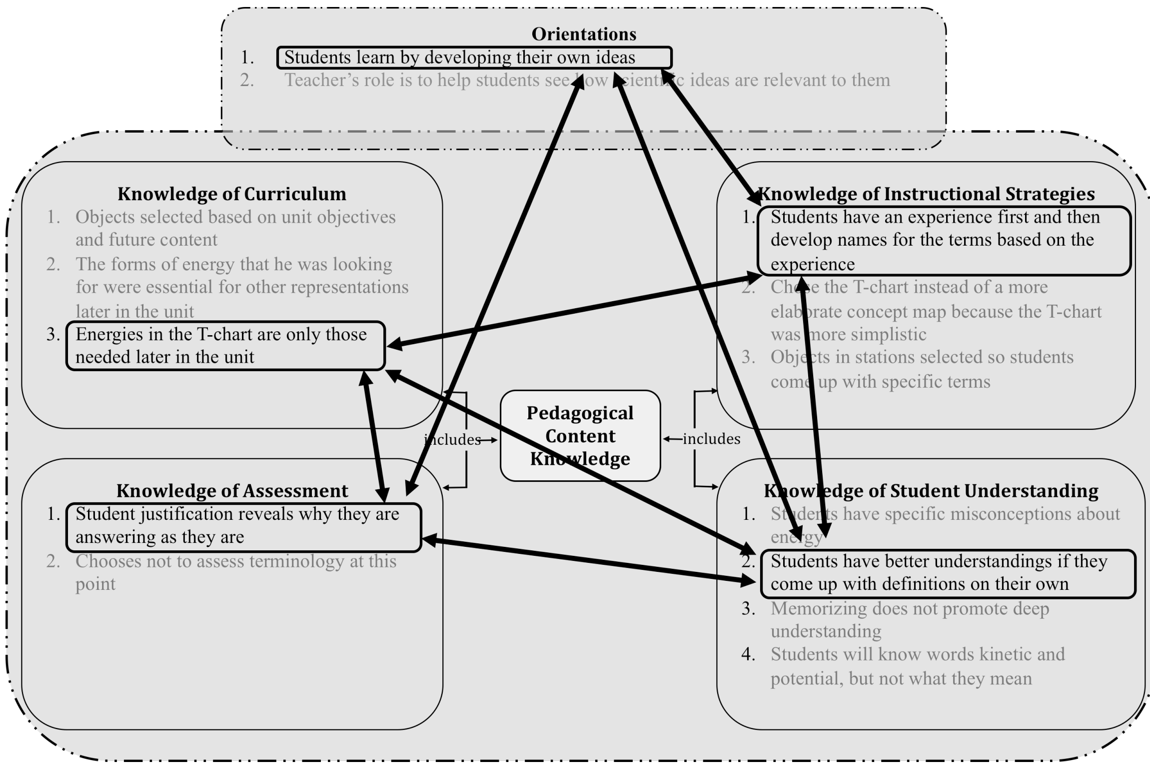

Figure 8. An example of the integrated nature of Jake's knowledge for using T-charts/vocabulary.

This description, and the corresponding figure, only captures a small slice of Jake's integrated knowledge for using T-charts/vocabulary for teaching energy. Similar connections between all five components of PCK are evident as a result of comparing Jake's instruction with the descriptions of his knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Findlay: T-charts/vocabulary

Summary of instruction. Findlay began the introduction to T-charts/vocabulary by asking the students as a group what they think of when they hear the word energy.

The students tossed out various ideas like “electricity” and “food.” She then made the point that in everyday language energy has many meanings, but that in physics it has a specific meaning. She then introduced the terms “system”, “initial state,” and “final state” using a PowerPoint presentation and asked the students to write the terms down in their notes. She then told the class that they were going to do a lab where they would visit different stations containing a variety of items (e.g. wind-up toys, baking soda and vinegar) and make observations, looking especially for the change from initial state to final state (she mentioned that this was like taking two pictures of an object and then comparing the two pictures). She then had the students set up a table in their notebooks to record their observations. Next, she demonstrated the first station (a bouncy ball) in front of the class and asked the students what they thought the system and the initial and final states were, emphasizing that the purpose of the lab stations was to “focus on how it’s different from before and after.” The students were then paired up and instructed to visit all of the stations. After visiting all of the stations, the students reviewed the ideas of states and systems by responding out loud to a question about a Jack-in-the-Box. Next, the students transitioned into taking notes on energy. The notes were on a PowerPoint presentation and the pattern for this portion of instruction was: 1) take notes on a form of energy, 2) come up with examples with a partner, and 3) discuss and elaborate as a class. The notes included forms of energy (e.g., mechanical), the energy form’s definition (e.g., energy of moving objects) and real-world examples (e.g., roller coaster). The students also generated real-world examples by reflecting in groups about each station’s activity and other life experiences that seemed to fit with the forms of energy. During this time, Findlay also elaborated on the students’ ideas and on the students' examples, including descriptions of how the phenomenon works (e.g., sound needs a medium) as well as other examples (e.g., light stick for chemical energy) and analogies (e.g., sound like dominoes). After taking notes on the forms of energy, the students participated in a PowerPoint energy review during which they responded to multiple-choice questions (e.g., what form of energy is stored in the bow) from their seats using ABC flash cards to respond. For a homework assignment, the students were assigned a reading page on kinetic and potential energy and asked to complete a worksheet where they classified the forms of energy from their notes as either kinetic or potential. On the next day, Findlay asked the class to review with her the terms potential and kinetic energy based on their prior knowledge from other courses and the homework they just completed. She then summarized that energy transforms from one form to another form and that all forms are either kinetic or potential. Next, the class was divided in half and they used the SMART Board to drag a list of the nine forms of energy to the correct potential or kinetic column on a T-chart, lining up and doing it as a race. Using the SMART Board, they were able to check their answers by pressing a button and if they were wrong, the T-chart reset and they had to start over. It took the class three tries to complete the T-chart. Then she led the class in a discussion about "why they are where they are," working through the list of kinetic energies and asking the students what was moving (based on their notes and the lab stations). Then she worked through the list of potential energies and discussed where the energy was stored (e.g., in the chemical bonds). Finally the students went back to their notes and added kinetic and potential designations to the energy forms that were already in their notes.

PCK for T-charts/vocabulary. The analysis of Findlay's interviews, regarding the sequence of instruction summarized above, resulted in a description of Findlay's knowledge in terms of the five components of PCK.

Knowledge of curriculum. At the end of this section of the unit, the students have had experiences with the types and forms of energy and they have the energies organized and defined in their notebooks. When asked why Findlay started the unit this way, she explained:

> Instead of taking everything as one big ball of wax, I am taking what you need to do to get to the end, and I am breaking it down into okay, let's learn the energies first and practice those. Then let's take those energies and use them in transformation then let's take those energies and make pie charts…The state objective is that they know the types and forms of energy.

This statement reveals that Findlay's decision to begin the unit by identifying the types and forms of energy was tied to her knowledge of the longitudinal curriculum, specifically, that the students will need to know the types and forms of energy later in the unit. Additionally, her curricular knowledge regarding goals is demonstrated in her reference to the fact that identifying the types and forms of energy is connected to the state objectives.

At other points in this section of the unit, the students are required to identify, versus memorize, the types and forms of energy. For example, the students begin with the lab stations and look for evidence of changes in energy and try to identify the form of energy. Findlay explains:

> It's not a memorization sort of thing. It's being able to identify, because that's one of our core curriculum things – to be able to identify different types and forms of energy…the objective is to have enough experiences so that they can have the different types and forms of energy and use them at will.

This example demonstrates Findlay's knowledge of curriculum in that her instruction is tied to the goals of the curriculum, specifically, that students learn to identify instead of memorize the types and forms of energy.

As a final example, when asked why she selected the specific items that she did for the lab stations, Findlay explains, "I laid all the types of energy that I knew I was going to cover and then I tried to have at least one lab station that touched on that energy." This example reveals that Findlay's decision to select the items that she did for the lab stations was informed by her knowledge of curricular resources, specifically, that particular objects were connected to the specific types and forms of energy that students needed to know later in the unit.

These examples, specifically, beginning by identifying energies first so that students are prepared for later representations, the goal of identifying (not memorizing) the types and forms of energy, and that the stations objects represent all the energy types in the unit highlight Findlay's knowledge of curriculum as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 9 at the end of this section.

Knowledge of instructional strategies. In the beginning of the unit, the students explored the lab stations followed by a discussion of their ideas as a class. Elaborating on this strategy, Findlay explains, "I wanted everybody to have a common experience that we could have discussions about." This example demonstrates Findlay's knowledge of sequencing instructional strategies, specifically, that the order of strategies relative to each other is important and that one strategy (lab stations) informs the next strategy (discussing ideas). This example also highlights Findlay's knowledge of the strength of the specific strategy.

Following the stations lab and the discussion about what the students observed, the students took notes. Explaining this decision, Findlay states:

> It's not like we take all these notes on these energies [and then] go to the stations and look for the energies. It was the other way around...my thinking was to have them see the value in what they've done as lab and make connections with this new information I was giving them to what they had done.

Again, this example demonstrates Findlay's knowledge of instructional strategies regarding the sequence of strategies (i.e., explore ideas before explain ideas), the strength of doing this (students make connections), and knowledge of an alternative sequence (explain before explore).

As a final example, students are assigned a reading page on kinetic and potential energy prior to any instruction from Findlay on these ideas. Findlay explains, "Their homework was to use their notes to figure out – in fact they had to read on their own the definition of kinetic and potential – so we were in essence checking our thinking, but they had already struggled. In this example, Findlay demonstrates her knowledge of purposefully using strategies to facilitate student learning, specifically, that reading about ideas prior to coming to class benefits student understanding and that she purposefully had students read after first exploring the ideas in class, but prior to the next day's class, so that they would struggle with the ideas.

These examples, specifically, that students have lab experiences first and make connections second, that the stations activity provides common experience for discussions, that the stations activity ties experiences/examples to energy types, and that homework provides opportunity for students to struggle with ideas before any explanation highlight Findlay's knowledge of instructional strategies as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Instructional Strategies" box in Figure 9 at the end of this section.

Knowledge of student understanding. Prior to turning students loose to complete the station exploration lab, Findlay modeled the first station of the bouncy ball for the students, walking them through the ideas of system, initial state, and final state and helping them decide how to write their observations in their lab notebooks. Findlay discusses this decision, explaining, "I want to build confidence. I want them to give me, I guess, more high school quality stuff." This statement reveals elements of Findlay's knowledge of student understanding regarding their ability levels and knowledge development, specifically that students are not confident when it comes to the exploration lab and that students will not provide high quality answers without some level of support first (e.g., modeling the first station).

During the stations exploration lab, the students investigated a variety of objects. Findlay selected two of the objects to demonstrate elastic energy, specifically, a Popper Topper (a small rubber disc that when turned inside out eventually reverts to it's original shape by "jumping" off of the table) and a wind-up toy (a plastic toy that the students wind-up and it walks across the table). Findlay explains that she selected these objects because:

> Stretchy things are generally pretty easy [for the students], so I thought that'd [Popper Topper] be easy to identify for elastic. But the springs in the windup things, I wanted to be sure to have that conversation…Kids that have broken those toys, they know. But not every kid does…I knew that that was a roadblock for some kids.

In this example, Findlay demonstrates her knowledge of student understanding regarding student confusion, specifically that most students recognize the Popper Topper as elastic energy because it is stretchy, but that they do not always recognize the wind-up toy as elastic energy because they are not aware that it is driven by a spring. This example highlights Findlay's knowledge that students are sometimes confused by certain station objects.

As a final example, Findlay introduces the T-chart in the form of a race, or competition, where students work as quickly as they can to assign the forms of energy to their corresponding type of energy. When asked about the decision to make this a competition, Findlay explained, "They [students] are competitive…I just learned how to do it the first year and then over time as it kind of cooked in the back on my head, I just like that we could make this a competition." In this example, Findlay demonstrates her knowledge of students' learning styles, specifically, that they are competitive and that she can support her instruction by providing opportunities for competition.

These examples, specifically, that students are not confident with exploration labs, that modeling helps students provide high quality answers, that students are sometimes confused by certain station objects, and that the T-chart race taps into student competitiveness highlight Findlay's knowledge of student understanding as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 9 at the end of this section.

Knowledge of assessment. During the stations exploration lab, the students are asked to write down their observations in their lab notebooks. Referring to one of the stations where students make two steel spheres collide, Findlay explains:

> The steel spheres one, I can't tell you the number of kids that thought that that was magnetic or electric. And it's not at all. I would never dream that they would say that. But because I'm having them write about it in their lab book, I'm discovering those things.

This example demonstrates Findlay's knowledge of an assessment strategy, specifically, that having students write their observations in their lab notebook helps to reveal their ideas.

As another example, during the time that the students were taking notes on the forms of energy, they were also instructed to come up with examples of the forms of energy with their partner. Findlay discusses this strategy, explaining:

> I asked them to go back to their lab to come up with examples for each type of energy, and that was just kind of my way of seeing that they're making the connections between what they did and what this new information or these new definitions are.

This example demonstrates another aspect of Findlay's knowledge of assessment strategies, specifically, that asking students to come up with examples of energy allows her to assess if they are understanding ideas and making connections.

These examples, specifically, that having students write their observations in their lab notebooks helps to reveal their ideas and that students generating examples of energy reveals their understanding highlight Findlay's knowledge of assessment as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Assessment" box in Figure 9 at the end of this section.

Orientations. Throughout Findlay's instruction, there are several instances where she provides a little groundwork before the students engage in an activity. For instance, before the students explore the lab stations, Findlay gives the students some terms that they will use in the activity (e.g. initial state). At another point, students are assigned a reading page on kinetic and potential energy before they discuss or use these ideas as a class. Both of these examples reflect one aspect of Findlay's orientation. Findlay explains, "The way that stuff was structured [in some curriculum materials]…is just try and figure it out a little bit. [That] was just too open ended I felt for the way I teach." This statement highlights Findlay's orientation regarding the role of the teacher, specifically, that the teacher needs to guide students to understandings.

Throughout her instruction, there are also instances where students begin with some sort of an experience. For example, the students explore the objects at the lab stations before they discuss the terminology for the energy forms. Findlay explains that this aspect of her orientation towards students' roles, specifically, that in general, students should begin with an experience, was "put into practice when I was doing a lot of literacy strategies" because she saw that it was "powerful and useful and more effective." This orientation of students beginning with an experience was demonstrated in Findlay's organization of the unit as a whole (e.g. the students began the unit by exploring the stations) but not necessarily in the organization of specific activities (e.g., she introduced the stations explorations activity by first discussing what the students were looking for and by demonstrating the first station).

Finally, throughout her instruction students are encouraged to discuss their ideas in light of their everyday experiences. For example, as the students are taking notes on the forms of energy, they are required to come up with real-world examples of the forms of energy with their partners. Findlay explains that when students do this, "They just walk out the door with a better understanding of their world." This example highlights another aspect of Findlay's orientation regarding the purposes of science teaching, specifically, that one goal of science education is that students have a better understanding of their world.

These examples, specifically, that classroom science needs to be structured, not just "here, figure it out," that students should begin with an experience, and that students gain a better understanding of the world highlight Findlay's orientation as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Orientations" box in Figure 9.

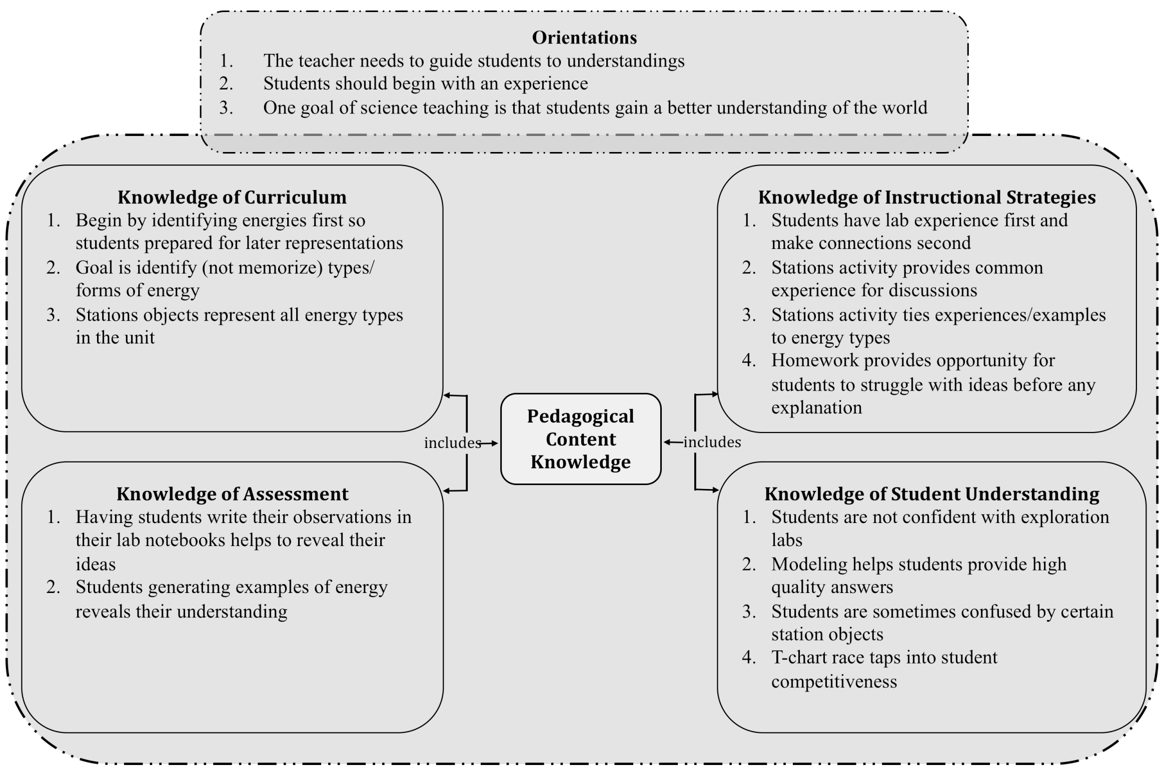

Figure 9. Examples of Findlay's knowledge in all five components of PCK for T-charts/vocabulary.

Summary of PCK for T-charts/vocabulary. Viewed collectively, the five components reveal the interconnected nature of Findlay's knowledge for using T-charts/vocabulary as a representation for teaching energy. For example, as captured in Figure 10, one aspect of Findlay's orientation is that students should begin instruction with a common experience. This orientation is reflected in Findlay's decision to start the unit with the stations lab instead of some other strategy (e.g., taking notes). However, Findlay's end goal with the stations lab is tied to her curricular knowledge that students need to identify the types and forms of energy earlier in the unit so that they can identify them using other representations later in the unit. This goal is reflected in her decision to organize the types and forms of energy using a T-chart. But, the way that she had the students construct the T-chart was informed by her knowledge of students, specifically that they are motivated by competition. Additionally, Findlay had the students explore the types and forms of energy in the T-chart by generating additional examples based on their experiences. This task served as a strategy for assessing the students' understandings and also connected to her orientation of students gaining a better understanding of the world.

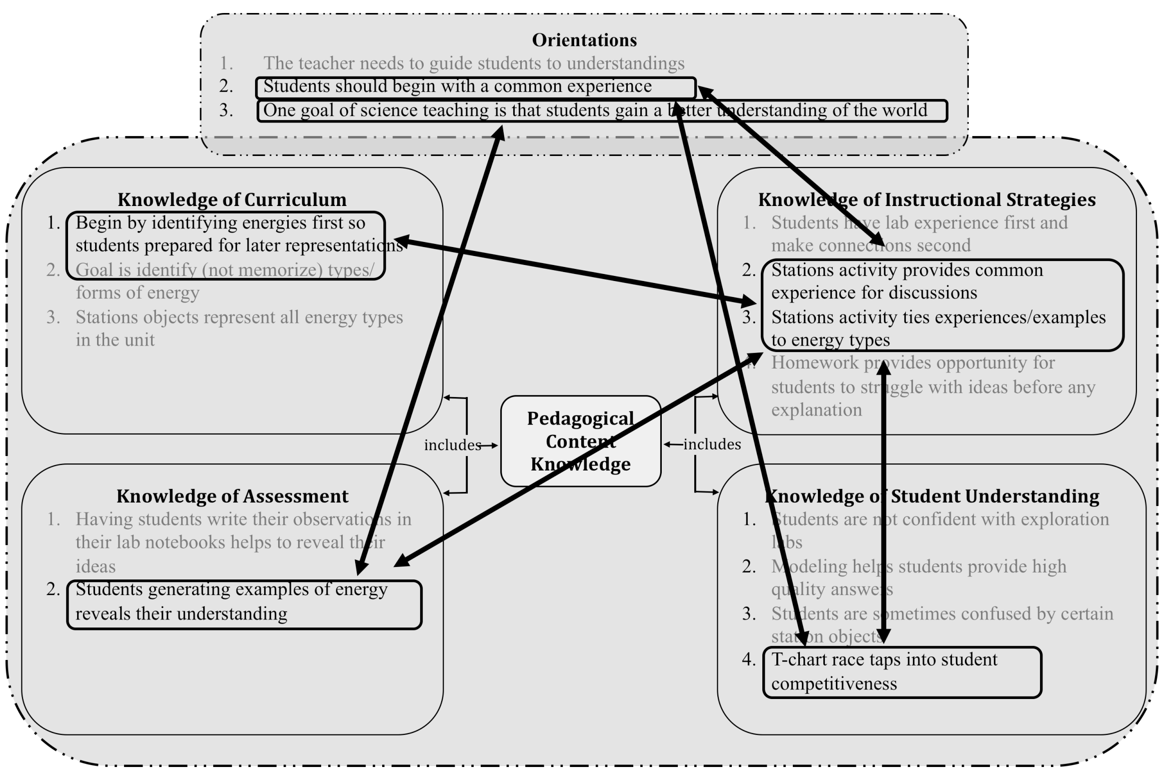

Figure 10. An example of the integrated nature of Findlay's knowledge for using T-charts/vocabulary.

This description, and the corresponding figure, only captures a small slice of Findlay's integrated knowledge for using T-charts/vocabulary for teaching energy. Similar connections between all five components of PCK are evident as a result of comparing Findlay's instruction with the descriptions of her knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Allie: T-charts/vocabulary

Summary of instruction. Allie began the introduction to T-charts/vocabulary by asking the class to consider a question on a worksheet regarding why roller coasters are designed so that the first hill is the tallest. But, before answering the question, Allie showed the class photos of roller coasters, asked probing questions about their design, and then showed a Point of View (POV) video of a roller coaster (a video from the perspective of being on the roller coaster). After they wrote down their ideas about the roller coaster, Allie asked the students what they remembered about the topic of energy from middle school. Then they discussed their ideas about the roller coaster question as a class, using the ideas about energy that they just discussed (i.e., from their previous science courses). Next, Allie used a PowerPoint presentation to give the students notes on energy, including the names of the forms of energy, the symbols for the forms of energy, their definitions, and examples of the energy forms in the real world. The notes were supported by video clips (e.g., a golf ball being hit in slow motion) and photos of the ideas (e.g., a light bulb). For homework, the students completed a reading about kinetic and potential energy and classified the forms of energy discussed in class as either kinetic or potential. On the next day, after discussing the ideas of potential and kinetic energy as a class, Allie asked for volunteers to come up to the SMART Board and drag the forms of energy that they just discussed into the corresponding kinetic or potential column on a T-chart. They then discussed as a class any problems that the students had with the location of any of the energies in the T-chart. After this discussion, Allie pressed a "check answers" button, which identified the energies placed in the incorrect column with red checks. Allie then led the class in a discussion about why the particular forms of energy were classified as either kinetic or potential (e.g., chemical energy is stored in chemical bonds). The students then fixed any of the energy forms that they had miscategorized on their homework. Next, the students reviewed the types and forms of energy by responding to multiple-choice questions using a Student Response System (students have individual keypads and submit answers to questions electronically). During the review, Allie presented a graph of the students' responses on the Smart Board determined by the Student Response System and they discussed these answers as a class. Finally, the students added the energy vocabulary to their notebooks, developing definitions as a group based on a class discussion about how they understood the terms based on their experiences up to that point in the instruction.

PCK for T-charts/vocabulary. The analysis of Allie's interviews regarding the sequence of instruction summarized above resulted in a description of Allie's knowledge in terms of the five components of PCK.

Knowledge of curriculum. Allie introduced this section of the unit by asking the students to respond to a question about the design of a roller coaster. This question was originally on a worksheet that Allie received as part of the Physics First curriculum. But Allie explained that she changed the worksheet from the original curriculum materials.

She explains, "Students didn't understand the wording, so it made no sense to them." This example highlights one component of Allie's knowledge of curricular materials, specifically, that curricular materials can be re-written to be more developmentally appropriate.

As another example of curricular knowledge, as the students were taking notes and writing down ideas about energy in their notebooks, they also included symbols for the types and forms of energy. Allie elaborates on the decision to include symbols at this point in the unit, explaining, "It's a short hand form that we are going to use later. When you're working on pie charts and that sort of thing, you don't want to write out the whole word the whole time." This example reveals Allie's knowledge of the longitudinal curriculum and what students will need to know later in the unit, specifically, that terms and symbols are important for future representations.

These examples, specifically, that the original curriculum materials can be re-written to be more developmentally appropriate and that the terms and symbols are important for future representations highlight Allie's knowledge of curriculum as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 11 at the end of this section.

Knowledge of instructional strategies. Allie started this section of the unit by showing the students a video of a roller coaster. When asked about this strategy, Allie explained, "It just pulls them into thinking. You trick them into thinking about stuff [phenomena related to energy] without really letting them know that you have made them think and you do it through this mental image [of the video]." This example demonstrates Allie's knowledge of how specific instructional strategies can promote student learning, specifically, that video clips pull students into thinking.

As another example, prior to asking the students to take notes on the types and forms of energy, Allie engaged the students in a discussion about energy, during which the students used terms that they were familiar with from middle school. And even after taking notes, the students continued to work with the terms through various activities (e.g., T-chart) and finally agreed on definitions for the terms as a class at the end of the section. Allie explains:

> The most important thing for me is for them to understand the concept behind what we are talking about. And you can call it these things, you can give it a vocabulary word, but do you understand the relationships between those words…you don't want it to sound so heady so they don't understand what you are saying...and eventually of course then you expect them to use the words.

This example highlights Allie's knowledge of sequencing instructional strategies, specifically, using strategies that facilitate discussion and exploration of energy ideas and concepts prior to introducing terminology.

These examples, specifically, that video clips pull students into thinking and the strategy of discussing energy ideas prior to introducing terminology highlight Allie's knowledge of instructional strategies as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Instructional Strategies" box in Figure 11 at the end of this section.

Knowledge of student understanding. Near the beginning of this section of the unit, Allie showed the students a POV video of riding a roller coaster. When asked why she did this, Allie explains:

> They like them and it's something that they feel like they're sort of experts in them, they understand things about them, they ride them, they've had experiences with them, or they at least are interested in them even if they've never really ridden one. So the reason I wanted to do that was, I wanted to bring potential gravitational energy in a way that they would get it.

This statement demonstrates an aspect of Allie's knowledge of student understanding regarding their prior knowledge and experiences, specifically, that students are familiar with roller coasters and they feel like they have some knowledge about them.

Throughout this section of the unit, Allie's emphasis was on the students developing solid understandings of the types and forms of energy so that they could use them later in the unit. When asked why she spent the amount of time that she did on the vocabulary, Allie explained, "They really have a hard time taking what they already know, being confident in it and applying it to new situations." This statement reveals Allie's knowledge of students' abilities and challenges, specifically, that students have a difficult time applying energy ideas to novel situations

As a final example, expanding on why she devotes class time to exploring and discussing the energy vocabulary, Allie explains:

> [Students are] not accustomed to using the vocabulary. Not accustomed to speaking in a way that you are using new words all the time and I think they are not comfortable with that. They would rather stick with the language they are used to.

This example highlights Allie's knowledge of student understanding regarding developmental levels, specifically, that students are not used to using the vocabulary, so they would rather not use it in class.

These examples, specifically, that students are familiar with roller coasters and they feel like they have some knowledge about them, that students have a difficult time applying energy ideas to novel situations, and that students are not used to using the vocabulary so they would rather not highlight Allie's knowledge of student understanding as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 11 at the end of this section.

Knowledge of assessment. During this section of the unit, the students worked towards being able to identify and distinguish between the types and forms of energy. The students explored their ideas of energy, considered what they knew from middle school, and learned new ideas through taking notes. Ultimately, the students were asked to make sense of these ideas by constructing a T-chart. Discussing the T-chart, Allie explains, "The [T-chart activity] I did in the beginning of the class today I felt like really exposed some of their thoughts about the differences [between potential and kinetic energy]." This example demonstrates Allie's knowledge of an assessment strategy, specifically, that using the T-chart helps to identify student thinking.

Allie also asked the students to show their understanding using a variety of approaches, including worksheets, class discussion, the SMART Board, the Student Response System, and lab notebooks. Discussing these strategies, Allie explains that the students show her that they:

> Understand this [energy] in so many different ways. And to me that is really effective. That changed me as a teacher when I got a chance to see that. I said, wow, that is really neat that we're asking them to do the same thing so many different ways.

This example demonstrates Allie's knowledge of an assessment strategy, specifically, that having students represent ideas in multiple ways allows students to reveal their understanding in multiple ways.

These examples, specifically, that using the T-Chart helps to identify student thinking and that representing ideas in multiple ways allows students to show understanding in multiple ways highlight Allie's knowledge of assessment as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Assessment" box in Figure 11 at the end of this section.

Orientations. Allie began the introduction to T-charts/vocabulary section of the unit by asking the students to consider the design of roller coasters. Prior to committing to any answers, the students considered the question in light of photos, videos, and a discussion about roller coasters. Responding to why she started this way, Allie explains, "I think it's in your heart, feeling that engagement is important." This statement highlights an aspect of Allie's orientation regarding the role of the teacher, specifically, her belief that teachers need to engage students in phenomena that can later be explained by scientific ideas.

As another example, after the students engaged in the question about why roller coasters are designed so that the first hill is tallest, they reviewed their prior knowledge about energy and then they took notes on the forms of energy. Responding to why the students took notes at this point, Allie explains, "You have to give them a certain level of familiarity with something…without background [e.g., vocabulary], to me, [future class activities] are really not very much use for kids at this level." Elaborating on this idea, Allie states, "I've learned the hard way that if you don't do the foundational stuff, you go back and it costs you more time." These statements reflect another aspect of Allie's orientation regarding the role of the teacher, specifically, her belief that teachers need to provide some level of background (e.g., vocabulary) before moving on to more complex ideas (e.g., energy transformation).

These examples, specifically, that students need to be engaged in phenomena that can later be explained by scientific ideas and that teachers need to provide some level of background before moving on to more complex ideas highlight Allie's orientation as connected to her use of T-charts/vocabulary. These specific examples are captured in the summary statements in the "Orientations" box in Figure 11.

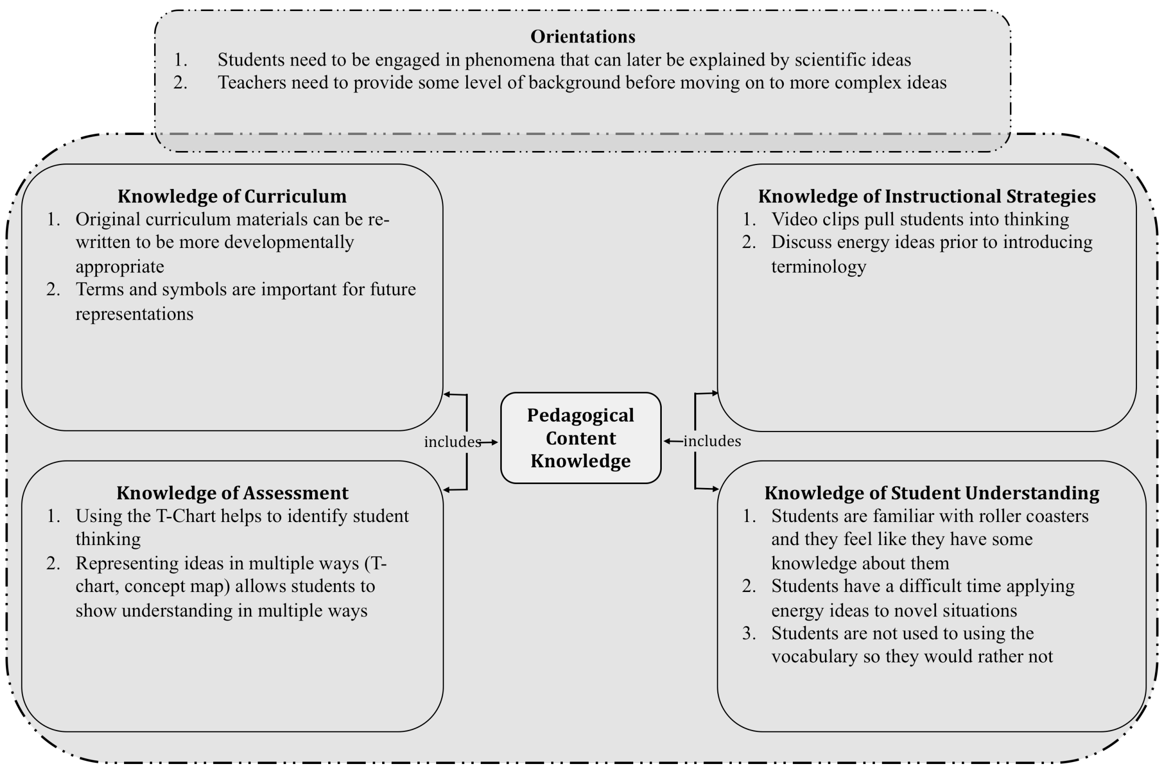

Figure 11. Examples of Allie's knowledge in all five components of PCK for T-charts/vocabulary.

Summary of PCK for T-charts/vocabulary. Viewed collectively, the five components reveal the interconnected nature of Allie's knowledge for using T-charts/vocabulary as a representation for teaching energy. For example, as captured in Figure 12, Allie holds the orientation that teachers need to provide some level of background for students before moving on to more complex ideas. This aspect of her orientation is reflected in her curricular knowledge that energy terms and symbols are important for representations that they will encounter later in the unit and that the curriculum materials supporting these ideas need to be written at developmentally appropriate levels. Because of this knowledge, Allie uses the strategy of engaging students in energy ideas prior to constructing a T-chart in order to help students develop this background knowledge early in the unit. But Allie also knows that students will have a difficult time applying their ideas about energy. Consequently, she gauges the level of student thinking, in part, by using the T-chart, so that she can determine if students are ready to move on to more complex ideas.

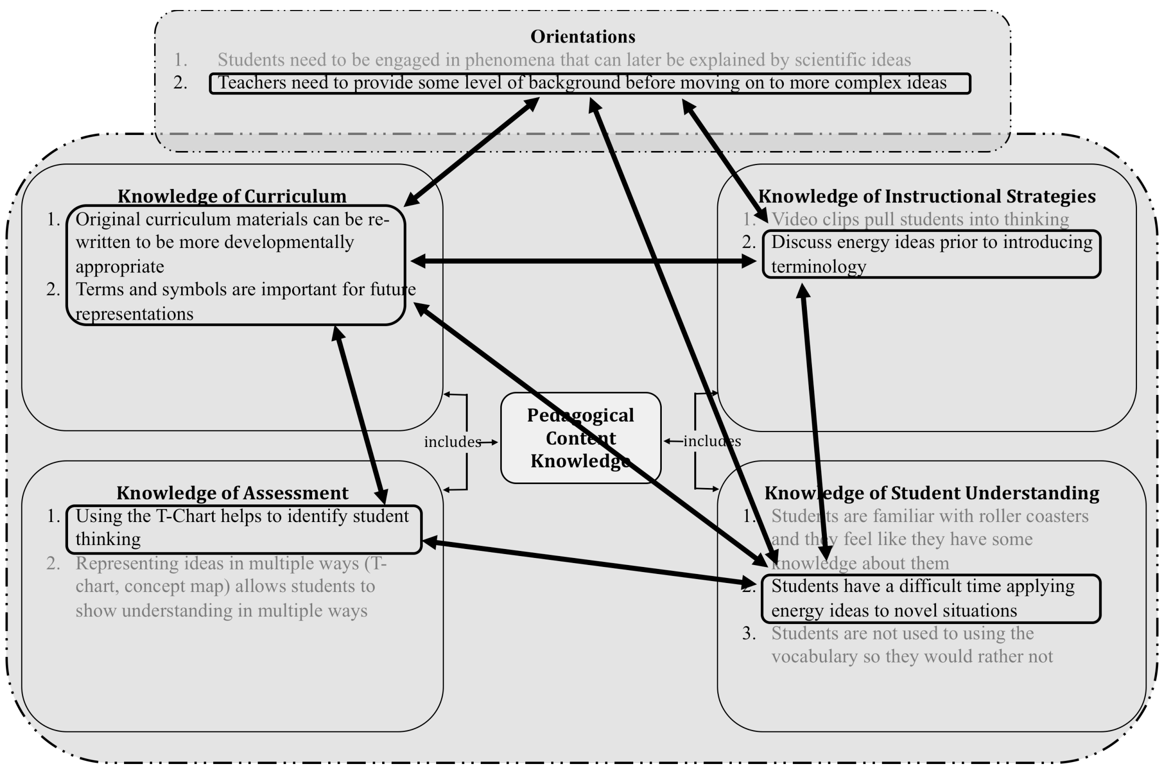

Figure 12. An example of the integrated nature of Allie's knowledge for using T-charts/vocabulary.

This description, and the corresponding figure, only captures a small slice of Allie's integrated knowledge for using T-charts/vocabulary for teaching energy. Similar connections between all five components of PCK are evident as a result of comparing Allie's instruction with the descriptions of her knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Jake: Pie charts

Summary of instruction. At the conclusion of his instruction on T-charts/vocabulary as summarized previously, Jake's students constructed a T-chart of the energy types and forms and then wrote down the final T-chart in their notebooks. After discussing the concept of energy transformation in greater detail and exploring the ideas of initial state, final state, and systems, Jake introduced the students to pie charts by asking the class to consider the scenario of a tennis ball being dropped from rest, from the perspective of energy transformation. The class responded that the tennis ball had gravitational energy at the top and kinetic energy at the bottom. Jake then asked, "What happens if I pick spots in between?" The class then discussed what the motion of the ball would look like at a location 1/3 of the way down and concluded that it would have both potential and kinetic energy. So Jake drew a pie chart at the top position and asked how much of the energy was potential, and they responded "all of it," so Jake labeled the pie as potential energy. Then he asked one of the students how much energy she would predict the ball had at 1/3 of the way down and she responded that 2/3 of the energy would be potential and 1/3 would be kinetic. Jake then drew and labeled the pie chart on the SMART Board to reflect this answer. Next, Jake asked a different student about the energy of the ball at 2/3 of the way down and another student about the energy at the bottom. He then brought up the point that he slipped the idea right by the students that the energy in every pie is always 100%, and he challenged the class with the question of whether it was even possible for the energy not to be 100%. Responding to this question, one student asked, "Isn't there some theory about that," to which Jake explained that it is called the Law of Conservation of Energy. He then discussed the Law in terms of the total amount of energy in the gasoline that people pump into a car equaling the total amount of energy that the car puts out. Next, the students worked as a class on a series of worksheet pie chart problems that required the students to construct pie charts one component at a time (e.g., size of the pies, type of energy in the pies, etc). As they worked through the problems as a class, they discussed the details about how to construct pie charts (e.g., where to write the symbols, how to denote slices). After working the pie chart problems as a class, Jake asked the students to work on a pie chart problem independently while he walked around the room, looking at student answers and asking questions. Next, he brought the class back together to discuss the subtle differences that he observed between the answers that the students were writing down. He then worked the problem that the students just completed using the SMART Board, highlighting that the energy is always 100% and that they do not know the exact sizes or quantities of the pies, but that it is okay if their answers vary a little bit because they are okay with a little bit of ambiguity (e.g., because they do not know if the speed of a ball is exactly half at a position halfway to the ground). For homework, the students worked on a pie chart problem about a ball sitting on a spring sitting on a table. On the next day, a review of this question led to a discussion of where the class wanted to consider ground level (e.g., the table or the top of the spring). Through a discussion and solving the problem using both frames of reference, the class decided collectively to use the top of the spring as the ground level. The students then worked progressively more complex pie chart problems that required more than two slices of pie, included ideas of friction, and required students to address issues of frame of reference and ground level.

PCK for pie charts. The analysis of Jake's interviews regarding the sequence of instruction summarized above resulted in a description of Jake's knowledge in terms of the five components of PCK.

*Knowledge of curriculum***.** Jake introduced pie charts by connecting pie charts to the students' understanding of energy transformation using the scenario of a tennis ball falling from rest. But later in the unit, Jake used pie charts to introduce the Law of Conservation of Energy. Jake explains, "So it really, in my opinion, it just makes it really easy to go into the Law of Conservation of Energy because you always have 100%, which means what you start with is what you finish with." This example demonstrates Jake's curricular knowledge regarding the relationship between ideas investigated throughout the unit, specifically, his knowledge of concepts that are coming up in the unit (Law of Conservation of Energy) and the relationship between these concepts (i.e., between energy transformation, pie charts, and the Law).

As another example, during his instruction on pie charts, Jake did not require that the students draw the pieces of pie in exact proportions. Jake explains:

> The big idea is to show that energy is just transformed from one form of energy to another form of energy, but I also don't think it's important to know how much, just that it is, and that you see patterns in the energy.

This statement reveals an aspect of Jake's knowledge of curricular goals and purposes, specifically, his knowledge of the goals of this section of the unit (e.g., energy transformation) and his knowledge that at this point in the unit, the pie slices can be approximate because the goal of the unit is not on exact quantities but on patterns.

As a final example, Jake leads the class in a discussion about where they want to consider ground level as a class because the choice of ground level informs how the system is interpreted. Jake explains:

> Right now, I know that half are going to say the top of the spring and the other half are going to say the ground, so I am going to try to convince everybody that if it's at the lowest point that it can get, we're just going to call that ground level…So really, what I am trying to do is set it up for future problems to head off future problems.

In this example, Jake demonstrates his knowledge of the longitudinal curriculum in terms of the types of questions and problems that the students will encounter later in the unit and the concepts that they will need in order to solve those problems later on.

These examples, specifically, that pie charts connect concepts of energy transformation and the Law, that pie slices can be approximate because the goal of the unit is not on exact quantities but patterns, and that discussion of ground level prepares students to solve future problems highlight Jake's knowledge of curriculum as connected to his use of pie charts. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 13 at the end of this section.

Knowledge of instructional strategies. Prior to introducing the idea of ground level being relative, Jake assigned the students a homework assignment on which they were uncertain as to where to call ground level. Jake describes his reason for assigning this problem, explaining:

> The key is you still want them to try it but you know that they are going to make a mistake at a certain spot, which is good, because then the next day when they come in, they say 'wait a minute. I got stuck on this part right here.' Then we get back into awesome, that's exactly what I was hoping you would do…those are real teachable moments when everybody has hit that…it's almost like they have more stock in the answer and when that happens, you have deeper learning.

This example highlights Jake's knowledge of the purposes of using certain instructional strategies, specifically, that assigning challenging homework prior to any explanation or clarification promotes deeper learning.

As another example, Jake explains:

> Pie charts are an easy way for students to understand that the energy is actually changing throughout the course of the system…there's always four or five different pie charts, but the overwhelming common factor is that everyone of the pies is a full pie.

This statement reveals Jake's knowledge of the usefulness of pie charts as an instructional strategy, specifically, that pie charts help students understand changes in energy as well as ideas regarding conservation of energy.

As a final example, Jake introduced students to drawing pie charts by using the scenario of a ball falling from rest. In the scenario, Jake divided the path of ball into four positions (i.e., top, 1/3, 2/3, and bottom). Discussing the decision to break the path of the ball into four positions, Jake explains:

> It didn't matter [the exact position of each instance of the ball]. All I needed was I needed four circles. We needed to start with all gravitational and finish with all kinetic, and I needed to have at least two spots in the middle. And the easiest way to do that is to break it down into thirds.

This example demonstrates Jake's specific knowledge about the fundamental components needed to introduce pie charts, specifically that students need to see changes in energy in at least four positions (i.e., three is not enough and five or more is not necessary).

These examples, specifically, that assigning challenging homework prior to any explanation promotes deeper learning, that pie charts help students understand changes in energy as well as ideas regarding conservation of energy, that students need to see changes in energy in at least four positions, and using a specific problem for discussion of where ground level should be highlight Jake's knowledge of instructional strategies as connected to his use of pie charts. These specific examples are captured in the summary statements in the "Instructional Strategies" box in Figure 13 at the end of this section.

Knowledge of student understanding. Jake used a variety of scenarios throughout his instruction on pie charts. Some of the scenarios (e.g., the ball falling from rest) required that students have some understanding of how objects fall (i.e. how their speed changes). Discussing the scenario of the ball falling from rest, Jake explains:

> One thing for this is they have to know that the higher you drop it, the faster it goes. And the weird part is that I know that that's a big student misconception. And what I mean by student misconception is that there are a lot of kids who don't know that.

This example reveals Jake's knowledge of students and their misconceptions, specifically, that students have misconceptions about how objects fall.

As a second example, Jake uses the example of pumping gasoline into a car as an example of energy transformation and conservation. When asked why he used this example, Jake explained:

> They all have basic knowledge of putting gas in a car. They also have knowledge that gasoline has weight and they probably never realized though how much weight of the car the gasoline actually comprised of, but yet every week they have to fill back up. They think that the gasoline just disappeared, and what I'm trying to show with them is that it's not just gone, it's just been converted...it's something that they've seen in the past, but something they probably haven't ever realized in the past.

This example demonstrates Jake's knowledge of student experiences and his knowledge of ideas that they have likely never considered, specifically that students have experiences pumping gas but have never considered where the gas goes.

As a final example, Jake introduces the components of pie charts one at a time, starting with simple scenarios and a couple forms of energy and working up towards more complex scenarios. Jake explains:

> I just find that [if you] break it down into its simplest components and hit each component, and then you start putting these components together, start to build the structure, you'll find that it's a lot easier for the kids to understand.

This example highlights Jake's knowledge of students and how they learn scientific ideas, specifically, that students learn science ideas more easily if they are broken down into basic components.

These examples, specifically, that students have misconceptions about how objects fall, that students have experiences pumping gas but have never considered where it goes, and that students learn science ideas more easily if they are broken down into basic components highlight Jake's knowledge of student understanding as connected to his use of pie charts. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 13 at the end of this section.

***Knowledge of assessment*.** As already discussed, a central feature of Jake's instruction was to break concepts down into basic components and then build student understanding one component at a time. For example, during his instruction on pie charts, Jake walked around the room looking at student work while the students individually solved pie chart problems that required them to construct pies one component at a time (e.g., size of the pies, type of energy in the pies, etc). Discussing this idea in terms of assessment, Jake explains, "If students miss problems, you have to figure out why they missed them. And if you break it down into its most basic components, it becomes really easy to figure that out." This statement highlights Jake's knowledge of assessment strategies, specifically, that breaking ideas into components allows him to see exactly what ideas students are struggling with.

As another example, Jake often assigned the students homework problems and then discussed the problems the next day in class, as evidenced by the ball on the spring on the table example. But when he discusses the problems on the next day, he does not discuss every part of every problem. Jake explains:

> Every one of the homework assignments I kind of go through a few of them, but I always leave one or two for them to do. And those are the one or two that I'm really looking for...I'm looking for the one circle that I didn't do, so I'm looking for okay did they get it, and the neat part is they either do or they don't, but it's easy for me to identify. And then if they don't I make notes on it, I write it on there and say what about this, what about this? And so I get an idea of who is scoring what, who is figuring it out, who is not.

This example demonstrates another aspect of Jake's knowledge of assessment strategies, specifically, that he can select specific homework questions to determine student understanding.

These examples, specifically, that breaking ideas into components allows him to see exactly what ideas students are struggling with and that he can select specific homework questions to determine student understanding highlight Jake's knowledge of assessment as connected to his use of pie charts. These specific examples are captured in the summary statements in the "Assessment" box in Figure 13 at the end of this section.

Orientations. During Jake's introduction to pie charts, he automatically drew each pie as a full circle (i.e., an entire pie, 100%). But it was not until later on in the unit that he challenged the students with the question of whether or not each pie should be 100%. Jake explained that doing this made it easy for the students "To come up with the idea that energy is not created or destroyed, basically the Law of Conservation of

Energy." This example of students coming up with a scientific idea reflects an aspect of Jake's orientation regarding how students learn, specifically, his belief that students learn science by coming up with or constructing ideas.

As another example of Jake's orientation, the students develop understandings about pie charts one idea at a time. For example, students begin with the simple scenario of a ball falling from rest and then slowly progress to more complex scenarios that include ideas like friction. Jake explains, "If you try to throw out the details right off the bat, as well as try to identifying what types of energies are there, I think you're trying to get two concepts at the same time, and my philosophy of teaching is just to get one at a time." This example highlights another aspect of Jake's orientation regarding how students learn, specifically, that science ideas should be introduced one idea or component at a time.

As a final example, the need to identify ground level is an important component for solving more complex pie chart problems. To address this need, Jake assigned a homework problem that could be solved using more than one frame of reference for ground level and then discussed the answer with the students on the next day to determine where they would consider ground level as a class. Jake explains:

> What I'm trying to do is take the first homework assignment that they have to experience this and come up with a common judgment about which [frame of reference for the ground] we should pick…I'm trying to make the point that there is no right answer but that we want to have a common answer, so we are going to pick one, and then which one is the best answer is based on what we all agree on.

This example supports Jake's orientation regarding how students learn science in the classroom, specifically, that students learn by coming up with ideas and by reaching consensus as a group.

These examples, specifically, that students learn science by coming up with or constructing ideas, that science ideas should be introduced one idea or component at a time, and that students learn science by reaching consensus as a group highlight Jake's orientation as connected to his use of pie charts. These specific examples are captured in the summary statements in the "Orientations" box in Figure 13.

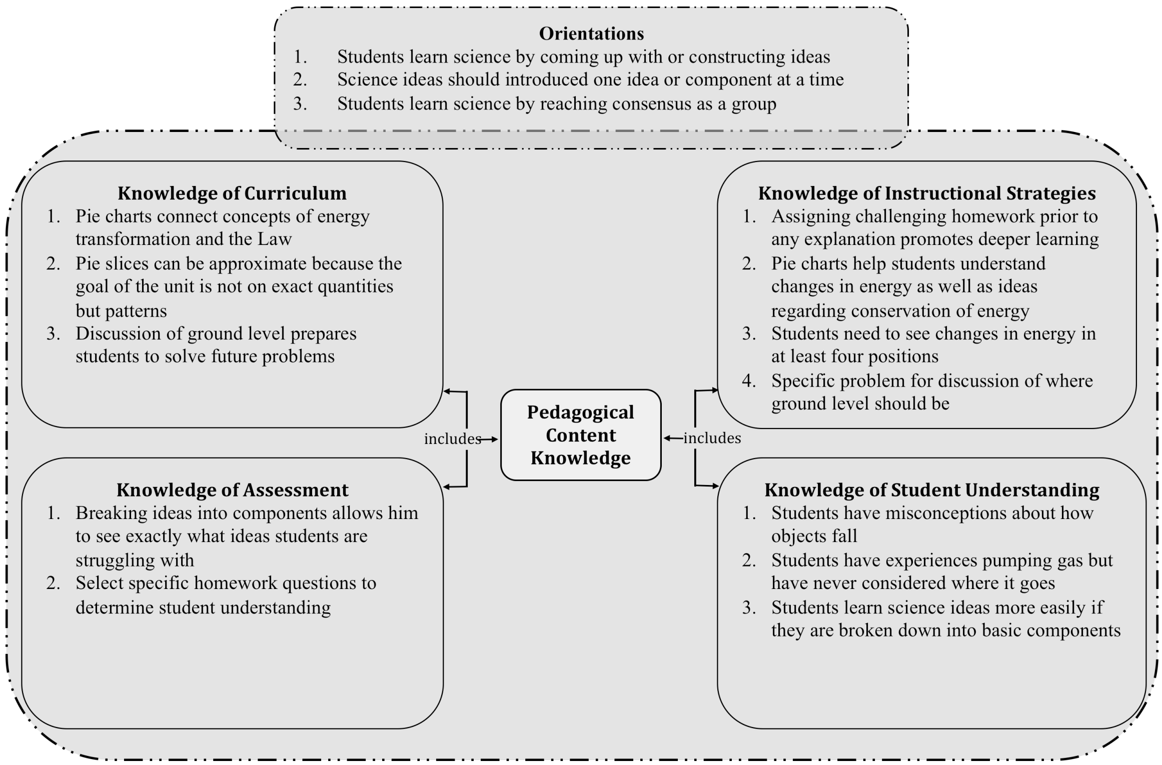

Figure 13. Examples of Jake's knowledge in all five components of PCK for pie charts.

Summary of PCK for pie charts. Viewed collectively, the five components reveal the interconnected nature of Jake's knowledge for using pie charts as a representation for teaching energy. For example, as captured in Figure 14, one aspect of Jake's orientation is that science ideas should be introduced one idea or component at a time. This orientation is reflected in Jake's instructional strategy of introducing pie charts one pie at a time using simple scenarios. But the motivation to break ideas down into smaller components is based on his knowledge of students, specifically, that students learn science ideas more easily if they are broken down into basic components and his awareness of the misconceptions that students have about the behavior of everyday objects (e.g., how objects fall). And because Jake breaks ideas down into smaller components, he is able to see exactly what ideas his students are struggling with. And ultimately, Jake's reason for selecting pie charts is his curricular knowledge that pie charts address the goals of the unit, specifically, that pie charts connect the concepts of energy transformation and the Law of Conservation of Energy.

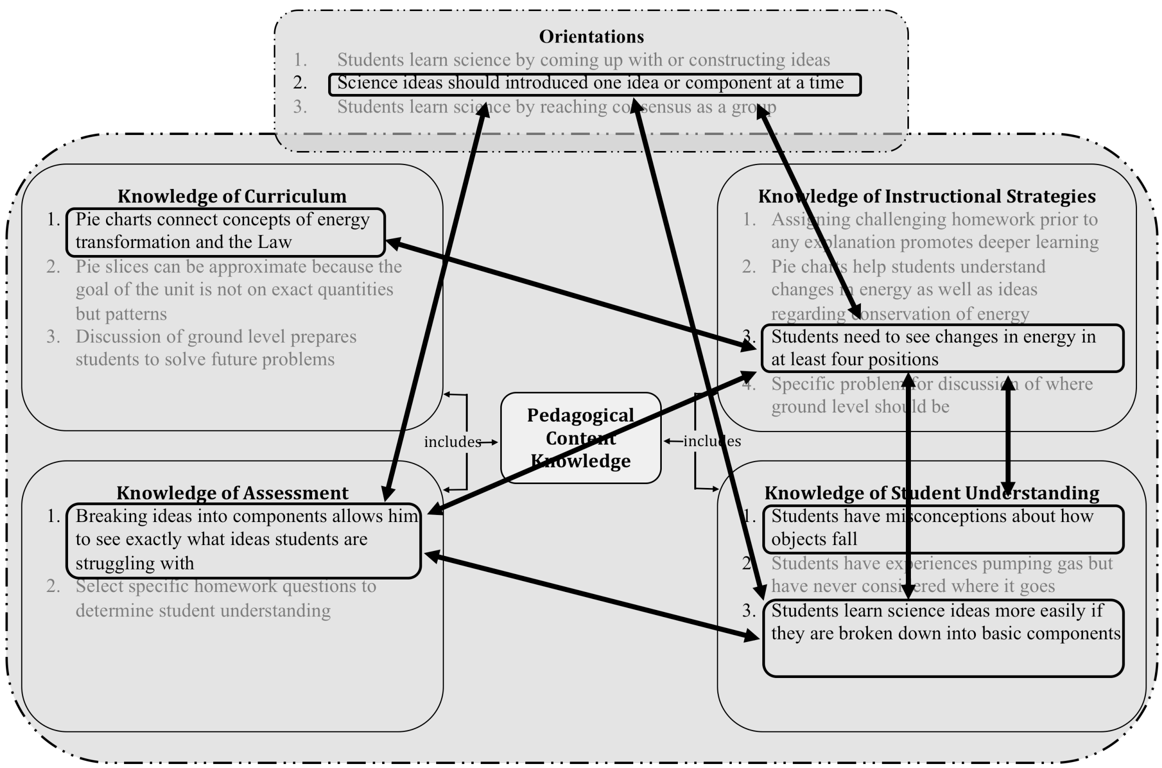

Figure 14. An example of the integrated nature of Jake's knowledge for using pie charts.

This description, and the corresponding figure, only captures a small slice of Jake's integrated knowledge for using pie charts to teach energy. Similar connections between all five components of PCK are evident as a result of comparing Jake's instruction with the descriptions of his knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Findlay: Pie charts

Summary of instruction. At the conclusion of her instruction on T-charts/vocabulary, Findlay had the students construct a T-chart of the energy types and forms by racing to see how fast they could do it. They concluded by adding kinetic and potential designations to the energy forms in their notes. After this, Findlay discussed the concept of energy transformation in greater detail with the students. To introduce pie charts, Findlay began with a brick pendulum demonstration, where she held a brick tied to a string tied to the ceiling (making a pendulum) up to a blindfolded student's nose and let it go. For their homework, the students were supposed to explain why the student did not get hit in the face with the brick. A discussion of their ideas on the next day led into a PowerPoint presentation designed as a modified version of a famous lecture/analogy about the Law of Conservation of Energy by the physicist Richard Feynman (Feynman, 1994). The students were challenged to try to figure out what each component of the presentation was analogous to in terms of energy. For example, the presentation involved a character from the television show *Family Guy* moving toy blocks in and out of his bedroom. In the presentation, the toy blocks represented energy and the bedroom represented the system. The PowerPoint presentation included multiple-choice questions about the analogy along the way, to which students responded using ABC flash cards. The questions were intended to help make the analogy components explicit (e.g., what do the blocks represent?). Next, Findlay introduced pie charts using a PowerPoint presentation and the scenario of a ball falling from rest. The motion of the ball was represented by images of the ball at three positions in its path (e.g., where it started at the top, 1/3 of the way down, and the bottom). Findlay had also drawn empty circles/pies next to each ball. She emphasized that the pies were all drawn the same size because they all have the same amount of energy. Then, the students were asked to talk to their neighbors about what kinds of energy they think are in each of the pies. The students responded to the question using their ABC flashcards (e.g., A. Kinetic, B. Potential, C. Both). The students then responded to another multiple-choice question about the percent of gravitational energy that the ball had at the top position, then to a question about the energy at the bottom position. For each question, the students generally provided the same answers. She used the SMART Board to facilitate a discussion about the types and amount of energy in the middle pie. After constructing the middle pie, Findlay asked the students to show on their fingers (1-10) how they feel about the difficulty of pie charts. The class then worked a series of pie chart problems as a class. As they work the problems, Findlay would point out key ideas and features of pie charts (e.g., sizes of pies, forms of energy). The pattern was generally: 1) the students try the problem on their own while Findlay walks around asking and answering student questions, 2) Findlay asks students to volunteer their ideas, 3) Findlay helps the class get the correct answer and discusses key ideas. The problems got progressively more difficult (e.g., including friction, beginning with more than one type of energy) and on some of the more difficult problems, Findlay would help the class by starting the first pie.

PCK for pie charts. The analysis of Findlay's interviews regarding the sequence of instruction summarized above resulted in a description of Findlay's knowledge in terms of the five components of PCK.

Knowledge of curriculum. Findlay's introduction to pie charts included a PowerPoint presentation designed as an analogy for ideas related to the Law of

Conservation of Energy. She also emphasized that pie charts are always 100%. Findlay explains, "They need to know that energy cannot be created or destroyed. It just gets changed to different kinds or transferred from one form…and that's one of our big overall things." This statement reveals Findlay's knowledge of curricular goals, specifically, her knowledge of the goals for the unit that students need to know the Law of Conservation of Energy.

The analogy presentation that Findlay used focused on toy blocks moving in and out of the character's bedroom. The blocks represented energy and the bedroom represented the system. Throughout the analogy, Findlay emphasized that they always had to have the same number of blocks in the room.   Findlay explains:

> I'm suggesting that energy can't be created or destroyed, I'm suggesting that energy is quantized with this silly analogy. So I think that that leads to what we do with closed and open systems for pie charts and things like that.

This example reveals Findlay's knowledge of the curriculum in terms of her knowing the concepts and ideas that occur later in the unit (pie charts, quantized energy) and her awareness of when in the sequence of the unit she can introduce these ideas.

As a final example, after learning the basic ideas about pie charts, the students practiced drawing pie charts as a class using a variety of different problems and scenarios. Many of these problems came from the original Physics First curriculum. But for some of the problems, Findlay redrew the sketches to make the ideas more clear. At one point, Findlay mentioned, "I redrew it [a pendulum problem]…so that I could see understanding." This example highlights Findlay's knowledge of existing curriculum materials and her knowledge of how to adapt those same materials to facilitate her instruction.

These examples, specifically, that students need to know the Law of Conservation of Energy, that the *Family Guy* analogy prepares students for pie chart ideas, and that redrawing some of the scenarios reveals student understanding highlight Findlay's knowledge of curriculum as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 15 at the end of this section.

Knowledge of instructional strategies. Findlay introduced pie charts using a pendulum demonstration. During the demonstration, the students observed a phenomenon (the brick swinging back and forth but never returning to its starting position). Their homework was to consider why the brick did not return to its starting position and hit the student in the face. Findlay explains:

> [The homework] was just something for them to walk out the door and have to struggle with a little bit so that when we come in and then I introduce pie charts it's like, I hope, anyway, I hope that they're able to make the connections and string it together.

This example demonstrates Findlay's knowledge of sequencing instructional strategies and ways to use particular strategies, specifically, that the pendulum demonstration and homework help prepare students for pie charts ideas.

After learning the basics of pie charts, the students practiced constructing pie charts using a series of problems on a worksheet. During that time, Findlay walked around the room and helped students with the pie charts. Explaining her approach, she states:

> First I like them just to figure out what kind of energies do you think we are working with. And then break it down picture by picture. So what do you think is here, what do you think is here. Once they can identify and do that, then we can start talking about like percentages and pieces.

This example demonstrates Findlay's knowledge of the instructional strategy of breaking ideas down a component at a time and walking students through that process.

Throughout her instruction on pie charts, Findlay also demonstrated several instances of guiding students to understanding by asking students questions. For example, when they explored pie charts for the first time, Findlay asked the students to respond to questions about what form of energy was in each pie at a specific position. Later on in the instruction, as the students practiced drawing pie charts, Findlay walked around the room asking the students questions about the types and amounts of energy in the pies. She explains:

> I try to ask them questions so that [pie charts] seem logical. Because I've found that if I don't do that, if I just say 'it's like this', then…you just can't learn it that way. They really are parrots. They really just want 'she said this, so I put this' and there's no rhyme or reason to it.

This example demonstrates Findlay's knowledge of the instructional strategy of asking logical questions in order to help students develop understandings about pie charts.

These examples, specifically, that the pendulum demonstration and homework help prepare students for pie charts ideas, breaking ideas down a component at a time and walking students through that process, and asking logical questions in order to help students develop understandings about pie charts highlight Findlay's knowledge of instructional strategies as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Instructional Strategies" box in Figure 15 at the end of this section.

Knowledge of student understanding. Findlay introduced pie charts using the pendulum brick demo. For the demonstration, she blindfolded a student, held the brick to the student's nose, and then let it go while the rest of the class observed. Explaining this strategy, Findlay explains, "It's more for the drama and the memory of them seeing that…I want to be able to refer to it and they remember it. And so I think that that's what I'm trying to make – memorable moments." This example demonstrates an aspect of Findlay's knowledge of students' learning styles, specifically, that they see the brick demonstration as dramatic and memorable.

As another example, Findlay describes student confusion with pie charts, explaining:

> For pie charts, you've got this amount [of energy]. And it's got to be 100% every time and so getting that, some kids, that concept isn't clear. They're just thinking these are circles and I just write the names in.

This example highlights Findlay's knowledge of students in two areas. First, Findlay recognizes that students are not clear on the concept of conservation of energy. Second, Findlay knows that some students do not see pie charts as representations of energy, but as circles in which to write answers.

As a final example, Findlay elaborates on using the *Family Guy* analogy, explaining:

> There are so many different kinds of learners and I wish they could all just think the sciencey way that I think, but they don't. Not every person is like me. So if they can't figure it out using the sciencey way that I'm thinking, well maybe they can use a goofy thing about the *Family Guy* characters to reason it out. So I guess that's just what I'm going for.

This statement demonstrates Findlay's knowledge of student understanding regarding learning styles, specifically, that students learn science in different ways and that students can understand the ideas in the Feynman lecture more easily through the *Family Guy* analogy.

These examples, specifically, that students see the brick demo as dramatic and memorable, that students are not clear on the concept of conservation of energy, that students see pie charts as circles in which to write answers, that students learn science in different ways, and that students can understand lecture ideas more easily through the *Family Guy* analogy highlight Findlay's knowledge of student understanding as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 15 at the end of this section.

Knowledge of assessment. During the instruction on pie charts, the students worked on some pie chart problems during class, while other problems were for homework. Comparing the class work to the homework, Findlay explains:

> I purposefully, you notice that this [worksheet] has four [pie charts], but [the example in class] only has three. Notice this one [on the worksheet] has three [pie charts] but it's reversed. I didn't want them just to copy what we did…there's not a big step between that [the example in class] and this [the worksheet], but the students that are copying and not thinking immediately stand out.

This example demonstrates an aspect of Findlay's knowledge of the strength of an assessment strategy, specifically, that the difference between scenarios in class and on worksheets reveals student understanding.

As another example, one of the scenarios that the students used to practice pie charts was tied to the pendulum demonstration that Findlay used to start class. Findlay discussed that she modified the problem from the original Physics First curriculum by shifting the positions of the pendulum. In the original problem, a pendulum was drawn at different positions along its path (e.g., at the start or top of its path, at the middle or bottom of its path, and at the end of its path). She explains, "I redrew it so that I knew I had 100% potential energy [at the top of its path], 100% kinetic energy [at the middle of its path], and 100% potential energy [at the end of its path]." She then explained that she shifted the position of the sketches at other points to highlight the distinctions in energy between the positions so that she could "see understanding." In this statement Findlay demonstrates an aspect of her knowledge of another assessment strategy, specifically, that redrawing some of the sketches/scenarios in the original curriculum helps to reveal student understanding.

As a final example, Findlay discussed how pie charts help her assess student understanding. She explains:

> You don't just put letters in circles randomly, and the kids who are parroters, those are the ones who you know put Pg for a box going across the table although nothing is ever going high or low. So either A, that told me that they didn't get it, they don't know their different energies, or B, they are just throwing letters into pies. They are not understanding what they are doing. They are not making connections.

This example highlights Findlay's knowledge of using pie charts for assessment, specifically, that the symbols that the students write in their pie charts reveal their misunderstandings.

These examples, specifically, that the difference between scenarios in class and on worksheets reveal student understanding, that redrawing some of the sketches/scenarios reveals student understanding, and that the symbols that the students write in the pie charts reveal their misunderstandings highlight Findlay's knowledge of assessment as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Assessment" box in Figure 15 at the end of this section.

Orientations. Findlay approached her instruction to pie charts using multiple strategies. For example, she started with a demonstration, transitioned to an interactive analogy, moved to a simple scenario of a ball falling from rest, and then constructed pie charts using ABC flashcards and the SMART Board. Findlay explains, “I guess I see there’s a tendency for me to take one idea and just hit it from a lot of different angles and then transition into the next one.” This comment reflects an aspect of her orientation regarding the role of the teacher, specifically, her belief that science teachers should hit ideas from multiple angles.

Findlay’s instruction on pie charts was also characterized by introducing ideas one piece at a time. For example, in the PowerPoint analogy based on *Family Guy*, the students considered each component of the analogy (e.g., bedroom = system, toy block = energy) one at a time. Findlay explains:

> You have to take it and you have to break it out into so what do I need to know to understand that, and then okay, what do I need to know to understand that, and just kind of break it down and work backwards, instead of just saying this is how you do it and be done.

This statement highlights another aspect of Findlay’s orientation regarding the role of the teacher, specifically, that teachers should break concepts down into basic components that build on each other.

As a final example of Findlay’s orientation, during the instruction on pie charts, Findlay asked the students to consider the types of energy that were present at the start of specific scenarios. Findlay explains, “I even did little cue things, like I pointed out that the word [*types* of energy] was plural so that they were thinking that okay, we can’t just come up with one.” This statement highlights Findlay’s orientation that the teacher’s role is to guide students to ideas instead of just giving them answers.

These examples, specifically, that science teachers should hit ideas from multiple angles, that teachers should break concepts down into basic components that build on each other, and guiding students to ideas instead of just giving them answers highlight

Findlay's orientation as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Orientations" box in Figure 15.

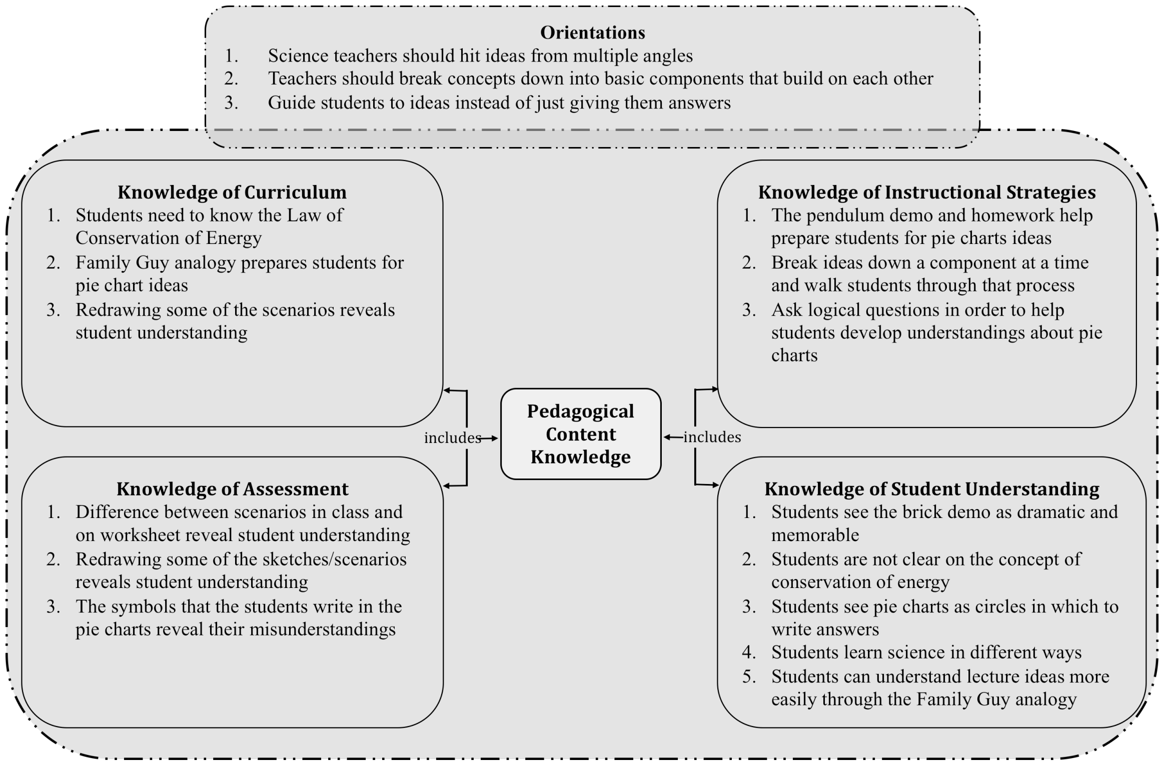

Figure 15. Examples of Findlay's knowledge in all five components of PCK for pie charts.

Summary of PCK for pie charts. Viewed collectively, the five components reveal the interconnected nature of Findlay's knowledge for using pie charts as a representation for teaching energy. For example, as captured in Figure 16, one aspect of Findlay's orientation is that teachers should break concepts down into basic components that build on each other. This orientation is reflected in Findlay's instructional strategy of walking students through the steps of building pie charts one component at a time. But the strategies that Findlay uses are also based on her knowledge that students learn science in different ways. Consequently, Findlay broke concepts down into basic components but introduced those components in various ways (e.g. demonstrations, interactive analogy, asking questions in a logical order). Additionally, Findlay assessed student understanding, in part, by re-drawing scenarios so that they were broken into components that revealed student thinking and by focusing on how the students labeled the pie charts. Ultimately, Findlay designed her instruction to address the curricular goals of the unit of students learning how to draw pie charts and connecting them to ideas of energy conservation.

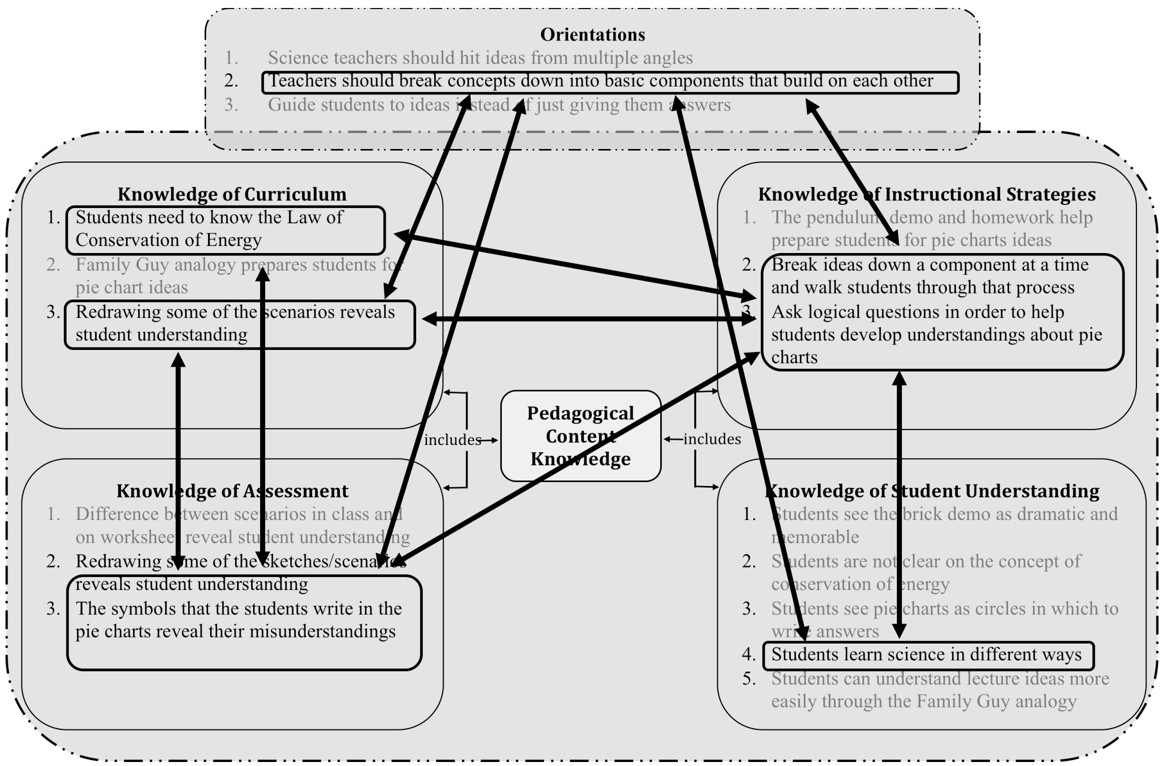

Figure16. An example of the integrated nature of Findlay's knowledge for using pie charts.

This description, and the corresponding figure, only captures a small slice of Findlay's integrated knowledge for using pie charts to teach energy. Similar connections between all five components of PCK are evident as a result of comparing Findlay's instruction with the descriptions of her knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Allie: Pie charts

Summary of instruction. At the conclusion of her instruction on T-charts/vocabulary as discussed previously, Allie asked the students to help her construct a T-chart of the energy types and forms and the students added the energy vocabulary to their notebooks after developing definitions as a class based on a class discussion about how they understood the terms based on their experiences up to that point. After the students completed a stations lab activity, shared their ideas from the experience, and worked on energy states and systems practice problems, Allie introduced pie charts by starting with the same PowerPoint presentation that Findlay used. The PowerPoint presentation was designed as a modified version of a famous lecture/analogy about the Law of Conservation of Energy by the physicist Richard Feynman. The students were challenged to try to figure out what each component in the presentation was analogous to in terms of energy. For example, the presentation involved a character from the television show *Family Guy* moving toy blocks in and out of his bedroom. In the presentation, the toy blocks represented energy and the bedroom represented the system. The PowerPoint presentation included multiple-choice questions about the analogy along the way, intended to help make the analogy components explicit (e.g., what do the blocks represent?). However, whereas Findlay used ABC flash cards to elicit student responses, Allie chose volunteers to answer the questions (she intended to use the Student Response System but it was broken) and then she elaborated on their answers. Following the presentation, the students watched a video of a Rube Goldberg machine (an apparatus designed to perform a series of energy transformations in a chain reaction) and were asked to "write down all the types of energy they see and the transformations." The students then shared their observations out loud with the rest of the class. On the following day, Allie introduced the students to a marble activity in which different colored marbles represented different forms of energy. During the activity, Allie discussed different scenarios with the class using the SMART Board and the students placed marbles corresponding to the energy of the object in the scenario (e.g., red marbles = the gravitational energy of a ball in the air) inside large circles drawn on a blank piece of paper. Then, the type of energy represented by the marbles was written in the middle of the circle. Next, they used a marker to divide the circles into slices of pie. Allie modeled this process using the document projector, asking the class questions along the way (e.g., what kind of energy do we have at the bottom?). Then, she showed a simulation of a roller coaster with and interactive pie chart corresponding to the changing energy of the coaster. After the simulation, Allie worked a second example with the class and then the students worked more marble problems by themselves or with partners while Allie walked around the room and answered student questions. Gradually, the students started solving the pie chart problems without the marbles, both in class and for homework. After checking homework answers and giving feedback to individual students as needed, the students worked a more complex pie chart problem on their own and then presented their solutions to the class using individual whiteboards (small dry-erase boards) on which they wrote their answers and then explained and justified their answers to the class. During the whiteboarding, Allie asked probing questions of the group and clarified ideas as needed.

PCK for pie charts. The analysis of Allie's interviews regarding the sequence of instruction summarized above resulted in a description of Allie's knowledge in terms of the five components of PCK.

Knowledge of curriculum. Allie began the introduction to pie charts with the *Family Guy* interactive analogy. She explains:

> It was to show open and closed systems, and it was to show the Law of Conservation of Energy – okay, if you start with this you have to end with this, what happened to the energy that's moving in and out of the system. Those were the kind of things that we were trying to accomplish.

This statement reveals Allie's knowledge of the curriculum, specifically her knowledge of the goals of the unit.

As another example, the students worked through a series of scenarios as they constructed and solved the problems in the marble activity and the scenarios progressed from simple to more complex. Allie explains:

> I put the roller coaster [problem] first on purpose because that's an easy one, and then I ended up saving [a different problem] for later because it was more complex and I needed some time to introduce the kinetic energy thermal idea...when I started [the unit], I used roller coasters and it was a nice return back to that.

In this statement, Allie demonstrates another aspect of her knowledge of curricular resources in terms of the sequence of scenarios on worksheets, specifically, that the marble activity scenarios were ordered in a sequence that helped build student understanding. This example also demonstrates Allie's knowledge of the longitudinal curriculum in terms of revisiting ideas introduced earlier in the unit (i.e., roller coasters).

These examples, specifically, that the *Family Guy* presentation addresses the unit goals, that the marble activity scenarios were ordered in a sequence that builds understanding, and revisiting the roller coaster ideas introduced earlier in the unit highlight Allie's knowledge of curriculum as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 17 at the end of this section.

Knowledge of instructional strategies. Prior to asking the students to draw pie charts, Allie showed the students a video of a Rube Goldberg machine and then had them do the marble activity. Allie discussed this sequence, explaining, "We're going to go from technology to something kinesthetic and then we're going to go to the pie charts…They can't just engage their head without doing something [kinesthetic first]." In this example, Allie demonstrates her knowledge of instructional strategies regarding the sequence of strategies, specifically, that the video-marbles-pie chart sequence helps to address the students' needs as learners.

As another example, Allie discussed her rationale for using the marble activity as a lead-in to drawing pie charts, explaining:

> I was looking for a bridge between just going from energy forms to going to pie charts. I felt like there was a step missing for a lot of the kids... the visual of the marbles was what's getting bigger, what's getting smaller, what forms are becoming more apparent here and what's going down. It just gave them something tangible to look at and something tangible to think about and instead of just abstractly saying it's this, this, this, you're actually giving them a mental representation of it to look at.

In this example, Allie demonstrates her knowledge of a strategy that bridges two concepts and its usefulness in facilitating student understanding, specifically, that the marble activity helps to connect the ideas of energy forms and pie charts by giving the students something tangible to work with.

As a final example, Allie discussed her rationale for using the roller coaster simulation with the interactive pie chart, explaining, "I like it because it has a running pie chart on it so the kids can see that... But I think that it's [also] useful as a visual aid because they remember it…they're so visual." In this statement, Allie demonstrates another aspect of her knowledge of instructional strategies regarding the purposes of using simulations, specifically, that the simulation of the pie chart provides a visual and lasting representation.

These examples, specifically, that the video-marbles-pie chart sequence addresses learners' needs, that the marble activity helps to connect the ideas of energy forms and pie charts by giving the students something tangible to work with, and that the simulation of the pie chart provides a visual and lasting representation highlight Allie's knowledge of instructional strategies as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Instructional Strategies" box in Figure 17 at the end of this section.

Knowledge of student understanding. Allie introduced the pie charts using the *Family Guy* PowerPoint analogy. She explains:

> It's a really simplistic, concrete presentation because you can see the blocks moving in and out. For those really concrete learners, you're going to get them with that but you're not going to get them with the pie charts as easily.

This statement highlights one aspect of Allie's knowledge of student understanding regarding learning styles, specifically, that some of her students are concrete learners so they need concrete representations.

As another example, Allie revisited the strategy of using the marbles activity prior to having the students draw pie charts, explaining, "The higher risk they [students] are, the most kinesthetic they are. That's what the research says. And you can see it." In this statement, Allie demonstrates her knowledge of student understanding in terms of the students in her class and their unique learning styles, specifically, that higher risk students are typically kinesthetic learners.

As a final example, Allie discussed the difficulties that students have with drawing pie charts, explaining:

> Kids get real stuck with the idea that, when they are drawing their pies, they really get stuck on how big the pieces are, how much do I give to each type of energy, and all that…It just got to the point where they were worried about the percentages more than they were worried about the concept.

In this statement, Allie demonstrates her knowledge of student understanding regarding specific difficulties that students have with specific representations, namely, that students get stuck on the idea of exactly how big the pieces of pie have to be and they lose the big ideas.

These examples, specifically, that some students are concrete learners so they need concrete representations, that higher risk students are typically kinesthetic learners, and that students get stuck on the idea of exactly how big the pieces of pie have to be and they lose the big ideas highlight Allie's knowledge of student understanding as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 17 at the end of this section.

Knowledge of assessment. At the end of this section of the unit, the students were asked to present the answers to selected problems using whiteboards. Allie explains:

> [Whiteboarding] just gives them another way to express what they know, which I really like. It also makes them accountable – they have to speak in front of a class, they have to answer my questions and kids' questions. It's a way for them to show what they know.

In this example, Allie demonstrates her knowledge of the purposes of a specific assessment strategy, specifically, that whiteboarding gives students the opportunity to show what they know while also holding them accountable for their work.

Discussing whiteboarding again, Allie explains that whiteboarding gets students to “Share with each other and justify what they’re thinking, which I really like. You know, justify your thinking, tell me why you think that.” This example demonstrates Allie’s knowledge of another benefit of using whiteboards for assessment, specifically, that whiteboarding provides opportunities for students to justify and explain answers.

As a final example, Allie discussed the strategy of walking around the classroom while the students worked on the marble activity, explaining:

> It was nice because I could walk around and I could look [at the students’ marbles] and that’s such a good visual for me just to be able to look over and go wow, no clue, or yeah that’s right. So that helped me a lot.

In this statement, Allie describes her knowledge of using a representation to assess student understanding, specifically, that the marble activity allowed her to quickly assess students.

These examples, specifically, that whiteboarding gives students the opportunity to show what they know while also holding them accountable for their work, that whiteboarding provides opportunities for students to justify and explain answers, and that the marble activity allowed her to quickly assess students highlight Allie’s knowledge of assessment as connected to her use of pie charts. These specific examples are captured in the summary statements in the “Assessment” box in Figure 17 at the end of this section.

Orientations. A central feature of Allie’s instruction on pie charts is her use of the marble activity prior to constructing pie charts on paper. Allie explains:

> A lot of times I just want them to, especially in the early stages, to put down the basics. Show me that you can do it. Once you can do it with marbles I'll leave you alone. But I want to see that you can do it…because if they can do it with the marbles, they can do it on the paper. Students need to begin with basic ideas first.

This statement reveals one aspect of Allie's orientation regarding how students learn science, specifically, that students need to begin with basic ideas first.

During her instruction on pie charts, Allie asked the students a lot of questions while they worked pie chart problems and asked them to justify their ideas. She also required the students to justify their ideas during the whiteboarding session. Allie explains, "I'm always trying to get them to justify, why did you put that, because sometimes they have a really good reason, and I don't see it." This example highlights another component of Allie's orientation regarding the role of the student, specifically, that one of a student's role in learning science is to justify his or her ideas.

As a final example, Allie uses the marble activity, in part, because the students are able to move the marbles around on the paper and that her students need this. She explains, "Because the higher risk they are, the more kinesthetic they are. That's what the research says. And you can see it. They have to be doing something to engage their head. They can't just engage their head without doing something." This example highlights another aspect of Allie's orientation regarding the role of the teacher, specifically, that the teacher's role is to address the needs of at-risk students by engaging students in doing something active.

These examples, specifically, that students need to begin with basic ideas first, that one of a students' roles in learning science is to justify their ideas, and that the teacher's role is to address the needs of at-risk students by engaging students in something active highlight Allie's orientation as connected to her use of pie charts. These specific examples are captured in the summary statements in the "Orientations" box in Figure 17.

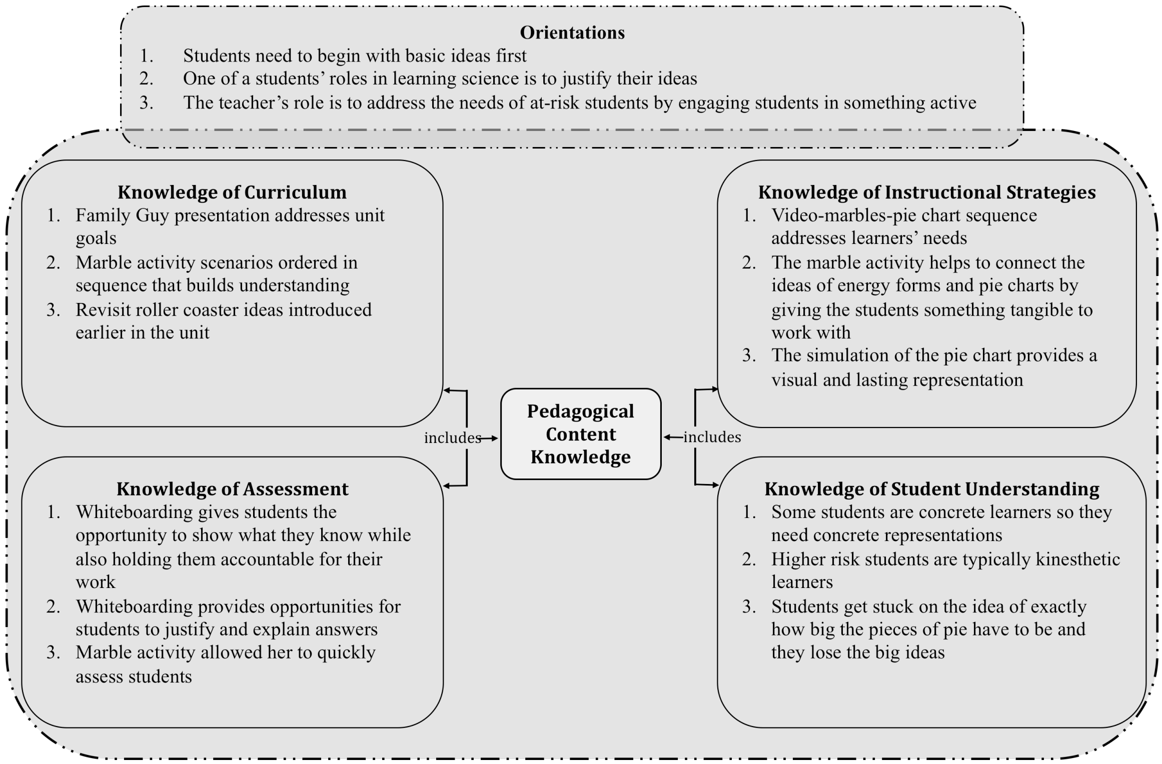

Figure 17. Examples of Allie's knowledge in all five components of PCK for pie charts.

Summary of PCK for pie charts. Viewed collectively, the five components reveal the interconnected nature of Allie's knowledge for using pie charts as a representation for teaching energy. For example, as captured in Figure 18, one aspect of Allie's orientation is that students need to begin with basic ideas first. This orientation is reflected in her strategy of beginning with a video followed by building basic scenarios with marbles prior to drawing pie charts. But this sequence of strategies was informed by her knowledge that her students are both kinesthetic and concrete learners. Additionally, Allie designed the marble activity to address her goal of students building understandings about pie charts. And because she used the concrete task of having the students build pie charts with marbles first, Allie was able to easily assess their understandings.

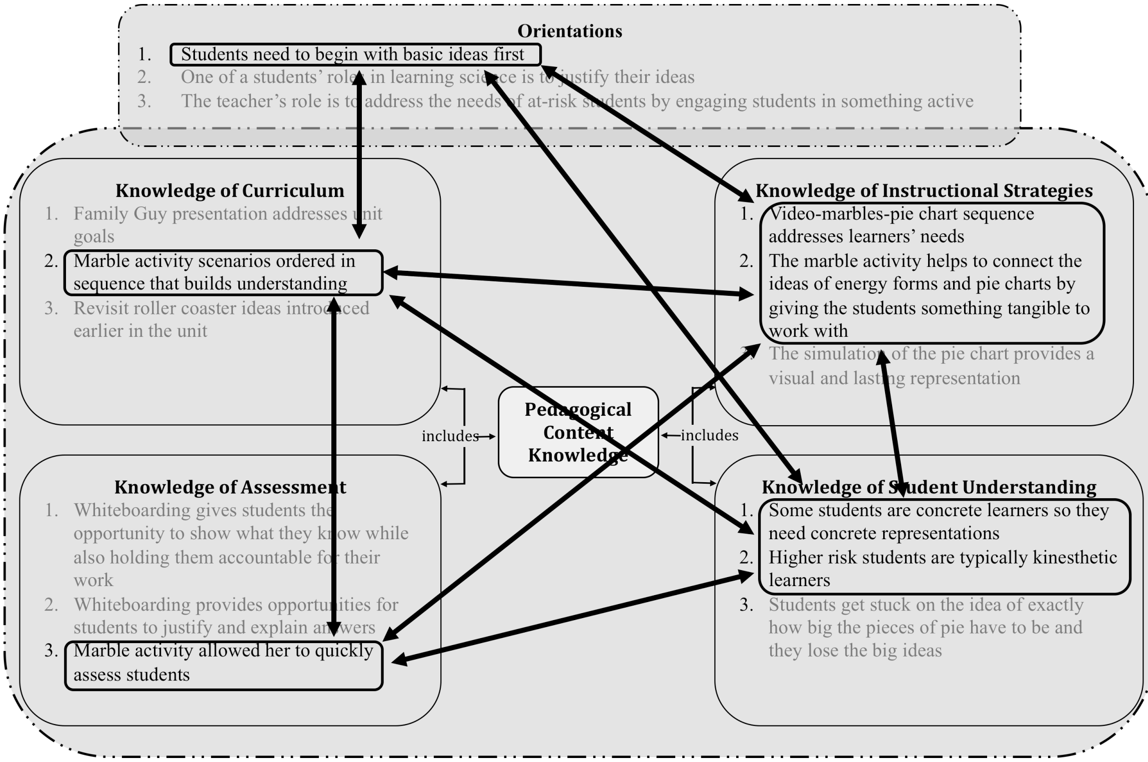

Figure 18. An example of the integrated nature of Allie's knowledge for using pie charts.

This description, and the corresponding figure, only captures a small slice of Allie's integrated knowledge for using pie charts to teach energy. Similar connections between all five components of PCK are evident as a result of comparing Allie's instruction with the descriptions of her knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Jake: Bar charts

Summary of instruction. At the conclusion of his instruction on pie charts as discussed previously, Jake's students had been introduced to pie charts and were assigned to work on progressively more complex pie chart problems. After working on more pie chart problems both individually and as a class, Jake introduced bar charts by beginning with a pie chart problem about a windup car from the students' homework. Jake started by reviewing the problem using the SMART Board, and then he asked the students to imagine that each pie gets only four pieces, "So every time we do this [consider an energy transformation scenario] you only get a quarter of a piece of a pie." He then stated, "Now let me show you how that relates to a bar graph." He then constructed a bar graph on the SMART Board and asked the class, "If I were to give each piece of pie, how much would you say each one should get…how much should each one of these [referring to the wind-up car problem] types of energy get?" One student then offered up an answer of two blocks elastic, one block kinetic, and one block thermal. Jake then drew the blocks on the bar chart on the SMART Board. Next, he introduced a dashed-circle between the two bar charts and explained that the dashed circle represented the system and that everything identified in the system was drawn inside of the dashed-circle. After this, he constructed a bar graph for the final state by asking the students to reason through their ideas about the forms of energy and how many bars they should draw. This led to a class discussion about the Law of Conservation of Energy and how the Law was demonstrated through the bar charts. Next, the students practiced working on a bar chart problem on their own while Jake walked around the room, observing their work and asking and answering questions. They then discussed the answer as a class, with Jake highlighting the key features of bar charts (e.g., number of bars/blocks, system circle, etc). They repeated this pattern for another problem. On the next day, Jake began class with a demonstration of the Law of Conservation of Energy where he made a pendulum, held it up to a student's face, and then let it go. He then asked the class for explanations as to why the student did not get hit in the face, pushing for more answers until he got an explanation based on ideas of energy conservation. Then he said, “Let’s do this again, only this time let’s push it” and the class responded excitedly, knowing that if Jake did push the pendulum, the student would get hit in the face. Jake then discussed the idea of adding energy to the system. He then asked the students to show on their fingers (1-5) how confident they felt up to this point, using this opportunity to clarify student questions. Next, he transitioned into solving work in/work out situations, using the same roller coaster problem that they had just worked but by selecting a different system that excluded parts of the original system. He then used the SMART Board to draw the dashed-system-circle, drawing everything in the system inside the circle, and everything not in the system outside the circle. He then drew a bar-like work arrow from outside the system circle to inside the system circle. This arrow was divided into four blocks, just like the bars that would be on the bar chart (Figure 19).

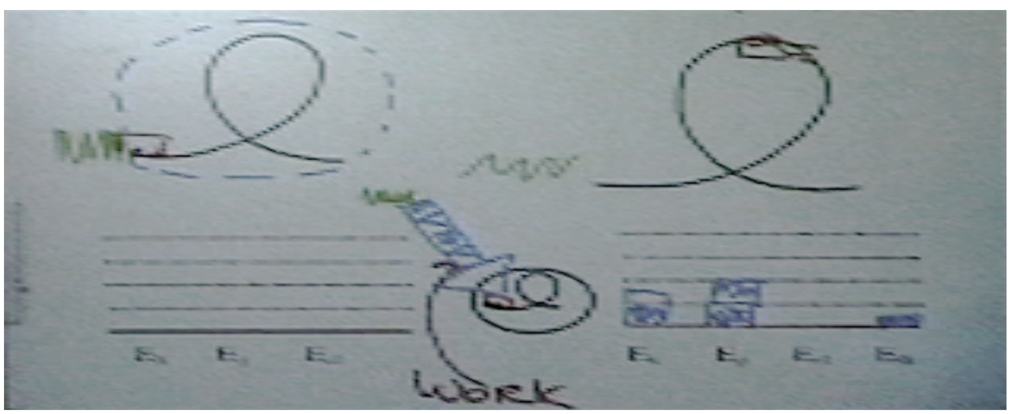

Figure 19. Bar chart in Jake’s class.

He then completed the final state side of the bar chart. Next, he worked a second example with the class, using the same scenario of a roller coaster and spring, but changing the system. He concluded class by working a few more problems with the class and by assigning more complex bar chart homework problems. On the next day, the students shared the answers to their homework problems using the whiteboards. During the whiteboarding session, the students were assigned a problem in pairs and asked to justify their solutions in front of the class.

PCK for bar charts. The analysis of Jake's interviews regarding the sequence of instruction summarized above resulted in a description of Jake's knowledge in terms of the five components of PCK.

Knowledge of curriculum. As previously discussed, Jake used a dashed circle to represent the system in the bar chart problems. But Jake also uses the same circle to identify systems in upcoming units. Jake explains:

> I know that it comes back up in the forces unit, but I'm not going to mention it now because it means nothing to them now…a good thing is that when we get into it in forces, this is such an easy idea, to identify what the system was in the energy unit, that doing it in the forces unit it is a piece of cake, and they'll understand.

In this example, Jake demonstrates him knowledge of the longitudinal curriculum, specifically, that the system circle used in the energy unit is also used in the forces unit.

As another example, Jake used the pendulum demonstration after discussing the Law of Conservation of Energy but before introducing the idea of work. Jake explains that he uses the demonstration to:

> Talk about how the Law of Conservation of Energy says that whatever you start with is equal to whatever you finish with…[but], when I push the ball, it's like adding energy to the system and so by adding energy to the system really what I'm talking about is work input.

In this example, Jake demonstrates his knowledge of addressing the goals of the unit, specifically, the goals of learning about the Law of Conservation of Energy and the concept of work.

As a final example, Jake recalled why he introduced the idea of a system early in the unit, explaining:

> You can't identify work unless you can identify the system first. So it's kind of like setting the stage for here are some things that you ought to know now but you probably don't understand why, but if you can pick it up now, then when I start saying these new words you'll be like oh yeah, I get this because I know what the system is.

In this example, Jake reveals his knowledge of the relationship between ideas investigated throughout the unit, specifically, that systems were introduced early in the unit so that students were prepared for bar charts.

These examples, specifically, that the system circle used in the energy unit is also used in the forces unit, addressing goals of learning about the Law of Conservation of Energy and the concept of work, and that systems were introduced early in the unit so students were prepared for bar charts highlight Jake's knowledge of curriculum as connected to his use of bar charts. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 20 at the end of this section.

Knowledge of instructional strategies. As previously discussed, Jake used the pendulum demonstration after discussing the Law of Conservation of Energy but before introducing ideas of work. But Jake explains, "You could either introduce [the pendulum] before the Law of Conservation of Energy or after it based on if you just wanted to talk about the Law or if you wanted to talk about work in and out." In this explanation, Jake reveals his knowledge about the multiple uses of a single instructional strategy, specifically, that the pendulum demonstration can be used to introduce or reinforce the Law of Conservation of Energy and the concept of work.

As another example, while practicing solving bar charts problems, Jake used the same roller coaster scenario in back to back problems. Jake explains:

> I did [the roller coaster problem] a second time where I took out the track part and it completely changed their answer. And so the two examples

> that I gave, one of them dealt with work that goes into the system, the other dealt with work that comes out of the system….And it was an easy way for me to bring in the idea of okay, this is work that is going into the system, this is work that is coming out.

In this example, Jake demonstrates his knowledge of using an instructional strategy to achieve two different goals, specifically, that changing the system on a bar chart problem changes the focus of the problem.

As a final example, Jake used the dashed circle to identify items in the system and items not in the system. Jake explains:

> When you start getting into work, if you take the spring and say okay, the spring is not in the system, and you draw it outside of the system, then it made it so much easier for me to teach, and in my opinion, the students to understand that it was the spring that was starting the whole thing off.

In this example, Jake demonstrates his knowledge of using an instructional strategy to facilitate student understanding, specifically, that actually drawing items that are part of the system inside of the dashed system circle (and vice versa) facilitates student understanding of bar charts.

These examples, specifically, that the pendulum demonstration can be used to introduce or reinforce the Law of Conservation of Energy and the concept of work, that changing the system on a bar chart problem changes the focus of the problem, and that actually drawing items that are part of the system inside the dashed circle facilitates student understanding of bar charts highlight Jake's knowledge of instructional strategies as connected to his use of bar charts. These specific examples are captured in the summary statements in the "Instructional Strategies" box in Figure 20 at the end of this section.

Knowledge of student understanding. Jake introduced the idea of identifying a system with a dashed circle earlier in the unit so that students would be prepared for bar charts. But he also explains that, "It's breaking it down into some of those basic components that just make it something that's sometimes difficult into something that is really easy." This example demonstrates Jake's knowledge of student understanding regarding student difficulties, specifically that identifying systems is sometimes difficult for students.

As another example, near the end of the unit the students were given progressively more complex bar chart problems. One of those problems focused on a swinging pendulum, and Jake explains, "The pendulum is actually a tougher problem than what they've been given so far. So once they get a better grip of the simpler problems, then I'll come back to this pendulum which is a little bit harder." This statement reveals Jake's knowledge of student understanding, specifically that some scenarios and problems are more difficult for students than others.

As a final example, Jake discussed the pace of the sequence of instruction on bar charts, explaining:

> If you take a look at your 5E model, it's okay how does that explain this part, how does that explain this part. Now that you've got that, let's take this a little step farther. So yeah, I think that's just natural that it does [that instruction speeds up and is a little more direct]. It really does. It seems like everything, once they get, if they have that good foundation. They key is that good foundation.

This example demonstrates Jake's knowledge of student learning, specifically, that students can learn at a faster pace and with more direct instruction once they have a good foundation.

These examples, specifically, that identifying systems is sometimes difficult for students, that some scenarios and problems are more difficult for students than others, and that students can learn at a faster pace and with more direct instruction once they have a good foundation highlight Jake's knowledge of student understanding as connected to his use of bar charts. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 20 at the end of this section.

Knowledge of assessment. After introducing bar charts to the class, Jake asked the students to hold up their fingers (1-5) to indicate how confident they were with bar charts at that point. For the students that revealed that they were not confident, he asked what was still confusing for them. Jake explains:

> When I asked where do you think that the weaknesses are in their learning, most of them, you can kind of tell that if they just had a little bit more repetition they would be there. And so that would be my goal, to make sure that they get enough repetition where they're going to feel comfortable.

This statement reveals Jake's knowledge of an assessment strategy and how it informed his instruction, specifically, that having students identify their confidence using their fingers helps to determine how to help them become more comfortable.

As a second example, Jake had the students whiteboard the answers to their homework problems at the end of the unit. At one point, he asked a group to indicate how their answer would change if their system was different. Jake explains, "I only do that [ask the presenters to change the system] because if I change the problem around just a little bit, and they can still solve the problem, then that means that they know what they are doing." This example demonstrates another aspect of Jake's knowledge of assessment, specifically, that asking students to modify problems during whiteboarding reveals their understanding.

These examples, specifically, that having students identify their confidence using their fingers helps to determine how to help them become more comfortable and that asking students to modify answers while whiteboarding reveals their understanding highlight Jake's knowledge of assessment as connected to his use of bar charts. These specific examples are captured in the summary statements in the "Assessment" box in Figure 20 at the end of this section.

Orientations. Throughout his instruction on bar charts, Jake followed a specific sequence in terms of introducing instructional strategies and concepts. For example, Jake introduced the pendulum demonstration prior to introducing the idea of adding work to a system. Jake explains:

> One of the things that I actually enjoy doing is thinking about sequencing, and really that's what that is, is identifying where is the best place to put this in to determine the best sequence that will bring about the best discussion or thought process or deeper thinking or whatever.

This statement highlights an aspect of Jake's orientation regarding the role of the teacher, specifically, that the teacher should sequence instruction to promote discussion and thinking.

As another example, Jake described why he spent the time that he did on bar charts, explaining, "I want the kids to know more. I always feel like I just want them to know a little bit more than, I don't know about everyone else, or just more than, I have higher expectations." In this statement, Jake reveals another aspect of his orientation regarding the role of students, specifically, his belief that his students should know more than other students.

As a final example of his orientation, Jake used a dashed circle to represent the system in bar chart problems, and the items that were part of the system were drawn inside of the circle. Jake explains, “If you stop and think about it, it just takes work and breaks it down into its basic components, and the way that it is set up is a way that I think is easier for the kids to understand than anything else.” In this statement, Jake demonstrates an aspect of his orientation regarding science teaching and learning, specifically his belief that breaking concepts down into basic components facilitates student understanding.

These examples, specifically, sequencing instruction to promote discussion and thinking, that his students should know more than others, and that breaking concepts down into basic components facilitates student understanding highlight Jake’s orientation as connected to his use of bar charts. These specific examples are captured in the summary statements in the “Orientations” box in Figure 20.

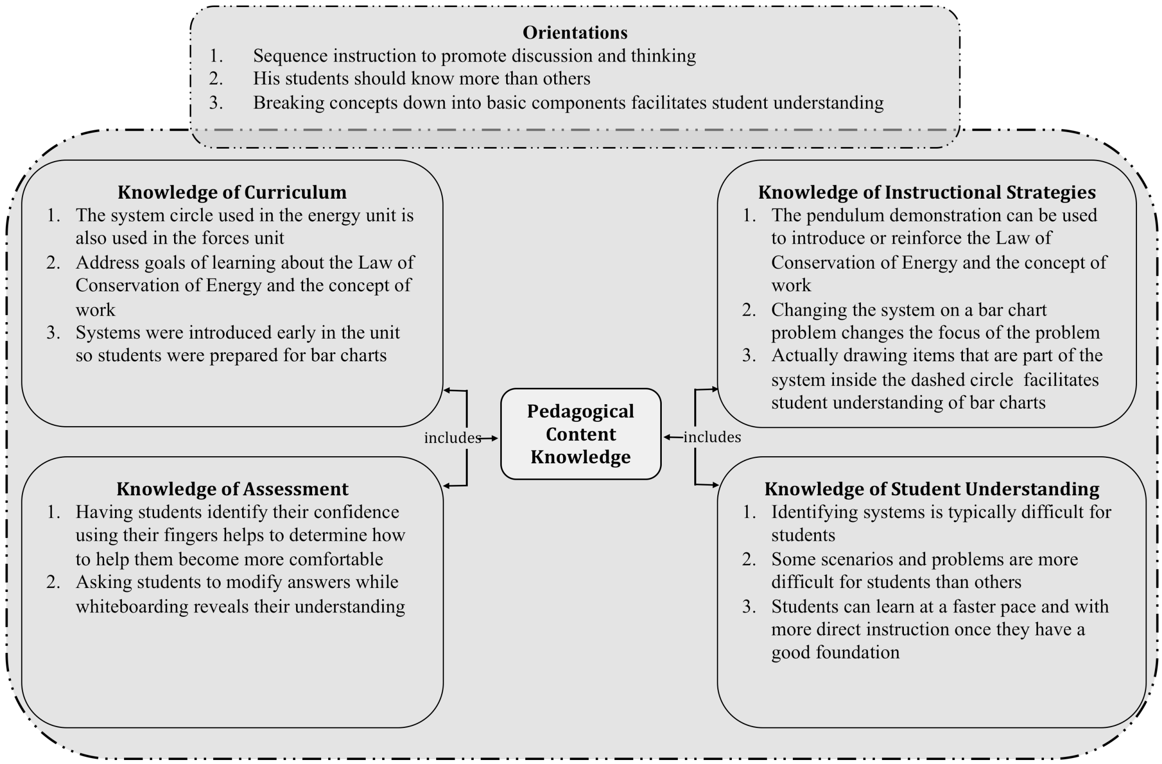

Figure 20. Examples of Jake's knowledge in all five components of PCK for bar charts.

Summary of PCK for bar charts. Viewed collectively, the five components reveal the interconnected nature of Jake's knowledge for using bar charts as a representation for teaching energy. For example, as captured in Figure 21, one aspect of Jake's orientation is that breaking concepts down into basic components facilitates student understanding. This orientation is reflected in Jake's strategy of breaking down systems by drawing the items included in the system inside the dashed circle and the items not included in the system outside of the dashed circle. But this strategy is also informed by his knowledge of student understanding, specifically that identifying systems is typically difficult for students, and he assesses their difficulties, in part, by asking students to identify their confidence by using their fingers followed by a discussion. And because of his curricular knowledge, Jake was able to introduce the dashed circle earlier in the unit and he was also able to use the dashed circle at the end of the unit to assess student understanding by having students modify their answers by moving objects in or out of the dashed circle.

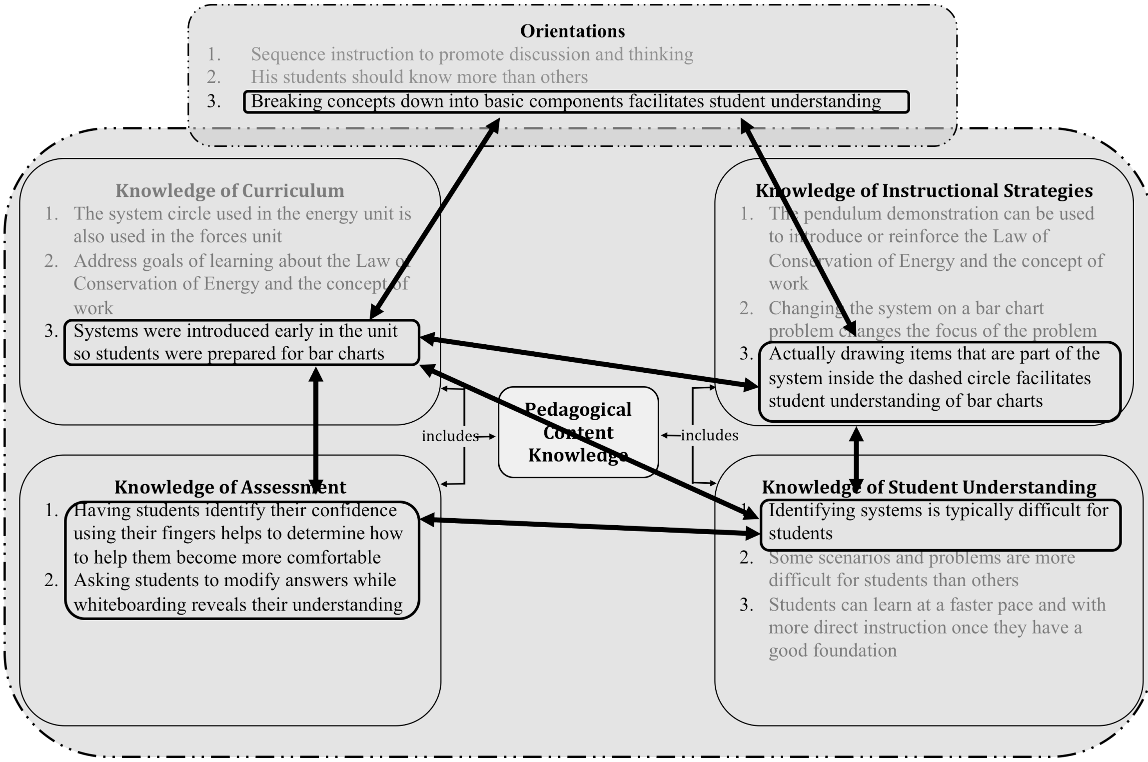

Figure 21. An example of the integrated nature of Jake's knowledge for using bar charts.

This description, and the corresponding figure, only captures a small slice of Jake's integrated knowledge for using bar charts to teach energy. Similar connections between all five components of PCK are evident as a result of comparing Jake's instruction with the descriptions of his knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Findlay: Bar charts

Summary of instruction. At the conclusion of her instruction on pie charts as discussed previously, Findlay introduced the students to pie charts and had the students work progressively more difficult pie chart problems. After working more pie chart problems individually and as a class, Findlay introduced bar charts by returning to the

Family Guy analogy PowerPoint presentation, but whereas the first *Family Guy* presentation focused on closed systems, this iteration of the analogy focused on open systems (i.e., systems where energy can come in or out). For this presentation, she followed the same pattern as she did for the first presentation, asking students to observe part of the story and then answer multiple-choice questions about the analogy using their ABC flash cards. At the conclusion of the presentation, Findlay introduced the idea of work. Part of this introduction to work involved having the students read colloquial uses of the term “work” and then voting as a class on the physics meaning of the term. Next, to introduce bar charts, Findlay gave each student a bar chart worksheet and then worked through the worksheet with the class on the SMART Board. First, the students drew pie charts for a scenario of a ball going up in the air and then back down and they discussed the pie charts to this scenario as a class (with a volunteer filling the pies in on the SMART Board in front of the class). Second, the class compared their pie charts to bar charts of the scenario that were already included on the worksheet. As the students compared their pie chart answers to the bar charts, they looked for similarities while Findlay pointed out the key ideas about the bar charts (e.g., how many bars, what form of energy, etc). Next, the students worked on another example individually, starting with pie charts, and then discussing their pie chart solutions as a class. Then, they constructed bar charts for the same scenario while Findlay asked leading questions and provided instruction on drawing the bar charts. Drawing the bar charts involved drawing a box around the system (there was also a system box between the bar charts), drawing bars for the initial state, and then drawing bars for the final state. They repeated this process for an open-system scenario and included a work arrow (drawn as blocks of energy entering into the system box; the arrow was labeled as "work in" and it included what was doing the work) (Figure 22).

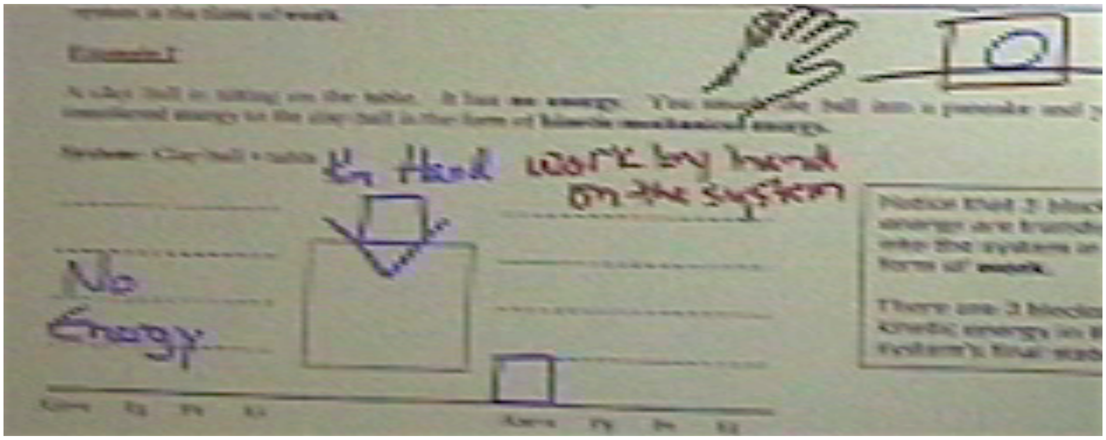

Figure 22. Bar chart in Findlay's classroom.

Findlay then worked on another open-system scenario with the class. On the next day, Findlay reviewed the students' bar chart homework with them by walking the class through her thought process of how she solves bar chart problems (by focusing on one component at a time and considering the energy in each component), asking leading questions along the way. The class then worked on finishing the rest of their bar chart homework from the day before while Findlay walked around helping the students. After grading their homework as a class, they practiced more bar chart problems in pairs for the rest of the period.

PCK for bar charts. The analysis of Findlay's interviews regarding the sequence of instruction summarized above resulted in a description of Findlay's knowledge in terms of the five components of PCK.

Knowledge of curriculum. In the original Physics First curriculum, systems were identified in the bar charts section of the unit using a circle. When Findlay taught bar charts, she used a box for the system. She explains:

> In the Physics First material, it is a circle in between the two bar charts from the initial and final state and what I found was kids were getting confused between pie charts and that circle…I realized I have this wonderful [*Family Guy*] analogy of the bedroom and we always tell them to draw a box around your system and that goes through even when you get into forces and everything, so why not just make it a box.

In this example, Findlay demonstrates her knowledge of the original curriculum but explains how and why she modified it and how the changes inform upcoming units, specifically, that changing the system circle to a system box helps distinguish between pie charts and system circles and the box is used to identify systems in the forces unit.

As another example, Findlay introduced bar charts by having the students work through a worksheet of bar chart problems. Findlay discussed that she developed the worksheet based on a reading that was in the original Physics First curriculum materials. She explains:

> We had a reading and we turned the reading into examples that they could work through. Then they had different homework and stuff and we turned them into examples and then we found a lot of their examples...some examples that were not that great or were too confusing or too complicated, so then we started just making up some of our own.

In this statement, Findlay reveals her knowledge of modifying and adapting curriculum materials, specifically, that she modified readings about bar charts into example problems that the students could work through.

As a final example, Findlay discussed how she structured her instruction throughout the unit to prepare students for complex bar chart problems, explaining:

> At the beginning with closed systems, I am trying to show that it is really not that different from what we have already been doing, it is just with a twist. Then, when we go to open systems again it is really not different from what we are doing, these take everything they have learned the whole unit and make them apply it all in one problem...it is really taking everything we did from those little charts where it says system, initial state, final state, energy to energy and it is taking all those things and it is

> just wrapping it up into one problem. So they are taking all the skills that they learned from the beginning and applying it right here.

In this example, Findlay demonstrates her longitudinal curricular knowledge of how ideas and concepts introduced in the beginning of the unit are connected to ideas introduced at the end of the unit, specifically, that concepts introduced throughout the unit were preparing students for the final bar charts.

These examples, specifically, that changing the system circle to a system box helps distinguish between pie charts and that the system circles and the box are used to identify systems in the forces unit, modifying readings about bar charts into example problems that the students could work through, and that concepts introduced during the unit were preparing students for the final bar charts highlight Findlay's knowledge of curriculum as connected to her use of bar charts. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 23 at the end of this section.

Knowledge of instructional strategies. Findlay began the introduction to bar charts by revisiting the *Family Guy* analogy. She explains, "So we go back to that analogy and we see energies leaving the system, energies coming into the system and the difference between open and closed systems." In this example, Findlay demonstrates her knowledge of the purpose behind using a specific strategy, specifically, that revisiting the *Family Guy* analogy allows the students to see the difference between open and closed systems.

As another example, Findlay explained why she designed the worksheet that she used to introduce bar charts in the way that she did, that is, with pie charts leading into bar charts. She explains:

> If I just said here is a ball going up in the air and then falling, this is what the bar chart would look like, it would seem for a lot of kids like this is just some new thing I have to memorize and not making the connection that no, we are showing the same ideas we have been doing [with pie charts], it is the same just with blocks. That was the point I was trying to get across to them is that this is not anything new, it is just showing it in a different way and we are going to see how this way has some advantages.

In this example, Findlay demonstrates her knowledge of the benefit of using the strategy of drawing pie charts first and then connecting the pie charts to ideas in bar charts.

As a final example, Findlay required that the students draw an arrow pointing into the system box to identify the work going into the system, and the students had to label the arrow to identify what was actually doing the work. Findlay explains:

> If I just let them call it work, then I was getting random thoughtless stuff written, instead of things that were logical and made sense…So, what I did I wanted to say what was doing the work on the system and you need to tell me what kind of energy it had that got transformed in order to do work on the system.

In this example, Findlay demonstrates her knowledge of using a specific strategy to support student thinking, specifically, that labeling the work arrow alleviates nonsense answers.

These examples, specifically, that revisiting the *Family Guy* analogy allows the students to see the difference between open and closed systems, drawing pie charts first and then connecting pie charts to ideas in bar charts, and that labeling the work arrow alleviates nonsense answers highlight Findlay's knowledge of instructional strategies as connected to her use of bar charts. These specific examples are captured in the summary statements in the "Instructional Strategies" box in Figure 23 at the end of this section.

Knowledge of student understanding. The focus of this section of the unit was on bar charts, but Findlay used pie charts to help introduce the bar chart ideas. Comparing the two, she explains, "They [students] like the bar charts better…they all tell me they like it better. I think it is because it is more quantitative, numbers of blocks, easy to count and easy to see and easy even to imagine." In this statement, Findlay demonstrates her knowledge of student understanding regarding their preference for certain representations, specifically, that students prefer bar charts over pie charts because they are easy to count and imagine.

As another example, Findlay discussed why she decided to use a box instead of a circle to represent the system, explaining:

> In the Physics First material, it is a circle in between the two bar charts from the initial and final state and what I found was kids were getting confused between pie charts and that circle. So when it first came up I was like where is this coming from and then as I got more into it I was like they think it is a pie chart that is embedded in the bar chart.

In this example, Findlay demonstrates her knowledge of student confusion regarding a certain representation, specifically, that students confuse the system circle with a pie chart.

As a final example, Findlay used a series of problems to give the students practice working with and drawing bar charts. Findlay elaborated on one of the problems, explaining:

> I knew they wanted to say sound and thermal and then be done. There is nothing wrong with that if that is what you want your final state to be, but if you read the reading that explains it all, that is not what it is supposed to be…if I let them go all the way to sound and thermal on that, then they are going to try to do that on other ones where I do not want them to do it.

In this example, Findlay reveals her knowledge of student confusion regarding a certain problem and she demonstrates her knowledge of the implications of not addressing that confusion in the beginning, specifically, that allowing the students to give a certain answer results in incorrect answers later in the unit.

These examples, specifically, that students prefer bar charts over pie charts because they are more concrete, that students confuse the system circle with a pie chart, and that allowing the students to give a certain answer results in incorrect answers later in the unit highlight Findlay's knowledge of student understanding as connected to her use of bar charts. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 23 at the end of this section.

Knowledge of assessment. Findlay introduced bar charts using the *Family Guy* presentation, and during the presentation, the students responded using ABC flash cards. Findlay explains:

> So we go back to that analogy and we see energies leaving the system, energies coming into the system and the difference between open and closed and they have their little ABC cards and they are telling what they think as we go and we check for understanding. Actually I want to say the idea of opened versus closed systems, everybody seemed pretty comfortable with that.

In this example, Findlay demonstrates her knowledge of an assessment strategy and what she learned from it, specifically, that having the students use the ABC cards revealed their understanding of open and closed systems.

As another example, Findlay helped the students develop understandings about bar charts by asking them questions based on questions she asks herself as she solves bar chart problems (i.e., focusing on one component at a time and considering the energy in each component). Findlay explains, "That was just my way originally of seeing kids having that trouble and trying to say well let's just break it apart a little bit more." In this example, Findlay demonstrates her knowledge of using a strategy to assess student understanding, specifically, that asking the students to solve problems one component at a time reveals the troubles that they are having.

These examples, specifically, that having the students use the ABC cards reveals their understanding of open and closed systems and that asking the students to solve problems one component at a time reveals the troubles that they are having highlight Findlay's knowledge of assessment as connected to her use of bar charts. These specific examples are captured in the summary statements in the "Assessment" box in Figure 23 at the end of this section.

Orientations. During her instruction on bar charts, Findlay required active participation from her students. For example, during the *Family Guy* presentation the students were required to answer questions using their ABC flashcards. Findlay explains that she wants to, "Get them more involved in the learning process instead of sitting there listening to me go on and on." This statement highlights an aspect of Findlay's orientation regarding the role of the student, specifically, that students should be actively involved in the learning process.

During the instruction on bar charts, the students started with a simple pie chart scenario, which led into a more complex closed-system bar chart problem, which led into a more complex open-system bar chart problem. Explaining this approach to introducing complex bar chart problems, Findlay explains:

> It does not seem as confusing, or at least I hope it does not sound as confusing, because they have just taken it in baby steps...So let's do something that is not very far from what we were doing, which is the pie

charts, doing the bar chart with a closed system, and then so now let's go to the next level once you are comfortable with that.

This example reveals another aspect of Findlay's orientation regarding how students learn science, specifically, that students should learn ideas one small piece at a time and build on each piece.

These examples, specifically, that students should be actively involved in the learning process and that students should learn ideas one small piece at a time and build on each piece highlight Findlay's orientation as connected to her use of bar charts. These specific examples are captured in the summary statements in the "Orientations" box in Figure 23.

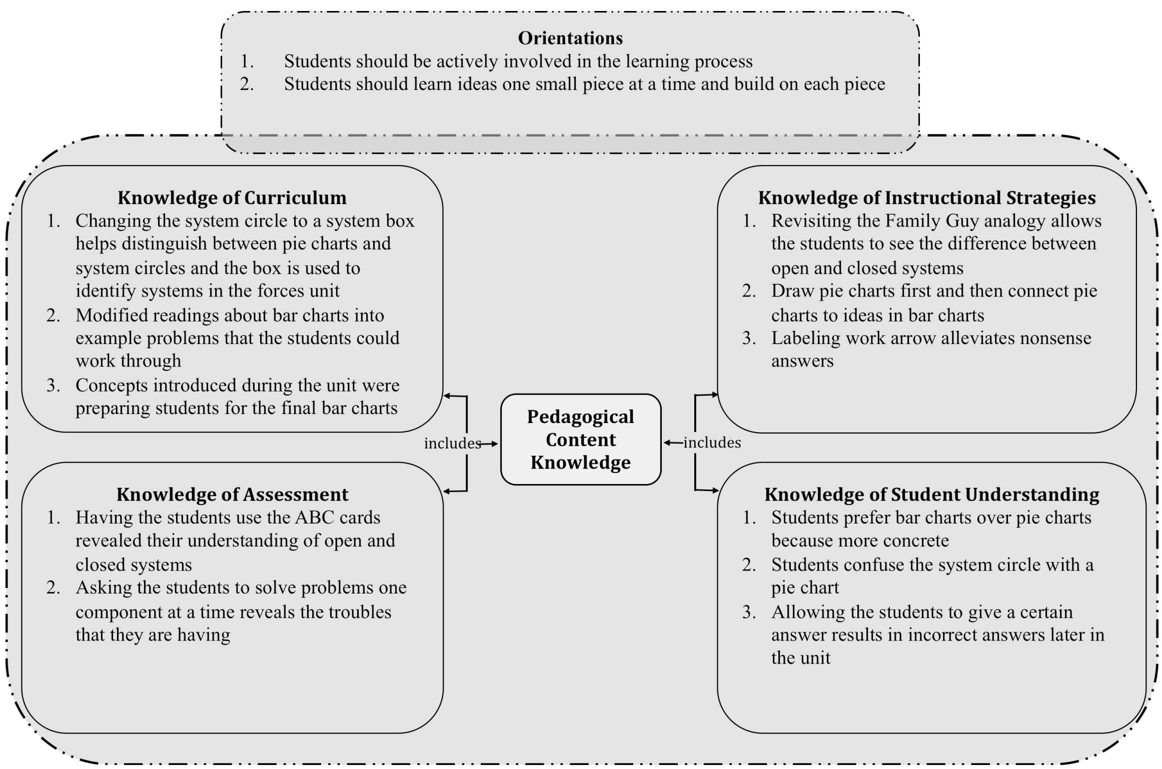

Figure 23. Examples of Findlay's knowledge in all five components of PCK for bar charts.

Summary of PCK for bar charts. Viewed collectively, the five components reveal the interconnected nature of Findlay's knowledge for using bar charts as a representation for teaching energy. For example, as captured by Figure 24, aspect of Findlay's orientation is the belief that students should learn ideas one small piece at a time and build on each piece. This orientation is reflected in her instructional strategy of introducing bar charts via pie charts using a worksheet modified from the original curriculum that started with pie charts and introduced bar charts one component at a time. Additionally, because of her knowledge of student understanding regarding students' confusion between pie charts and the system circle in bar charts, Findlay changed the system circle to a system box. Furthermore, while introducing bar charts one piece at a time, Findlay also used ABC flash cards to reveal student understanding of each piece.

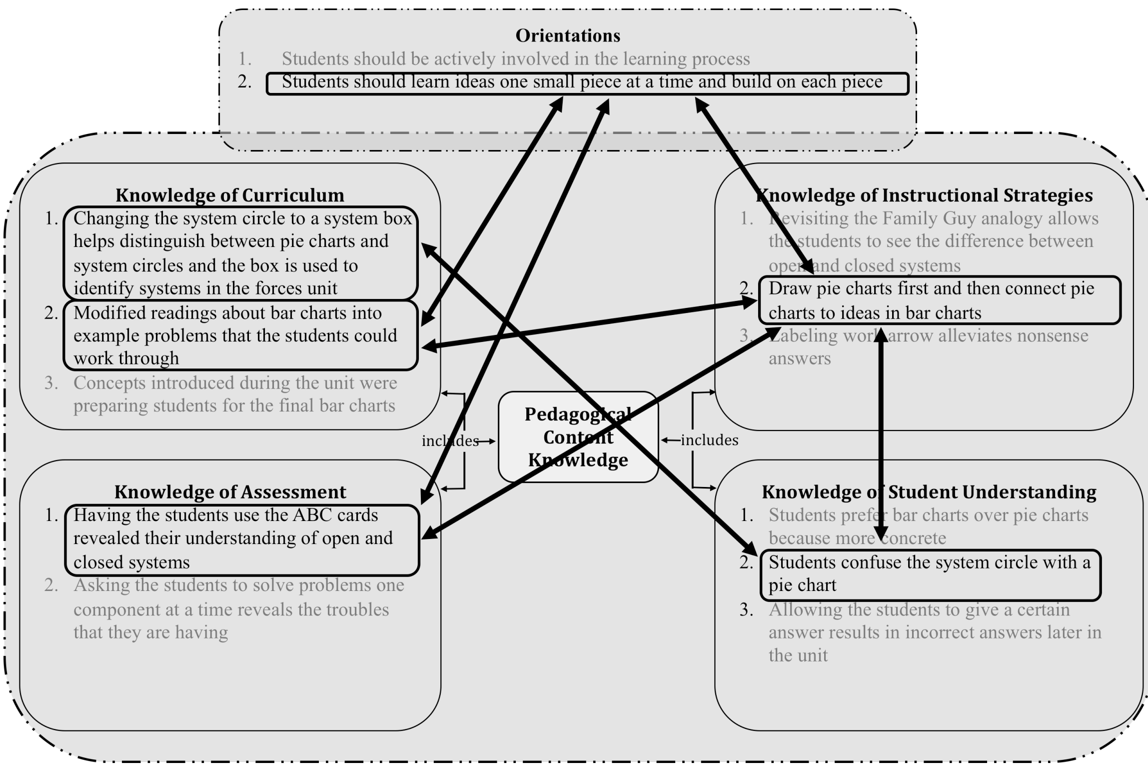

Figure 24. An example of the integrated nature of Findlay's knowledge for using bar charts.

This description, and the corresponding figure, only captures a small slice of Findlay's integrated knowledge for using bar charts to teach energy. Similar connections between all five components of PCK are evident as a result of comparing Findlay's instruction with the descriptions of her knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Allie: Bar charts

Summary of instruction. At the conclusion of her instruction on pie charts as discussed previously, Allie introduced the students to pie charts and had them work on more complex pie chart problem on their own and then present their solutions to the class using whiteboards. After this, Allie introduced bar charts by starting with a SMART Board presentation that described a scenario of a clay ball sitting on a table. The students were given a worksheet that matched the scenario and Allie built a case through class discussion that if her hand was not part of the system the ball would just sit there, but, in order to flatten the ball, she would have to have an open system and would have to do work on the ball. Next, she used the SMART Board to display a portion of the students' worksheet showing blank bar charts and asked the class how much energy the ball has if it is just sitting there. The students responded that it does not have any energy, so Allie wrote "no energy" over the first, empty bar chart (Figure 25).

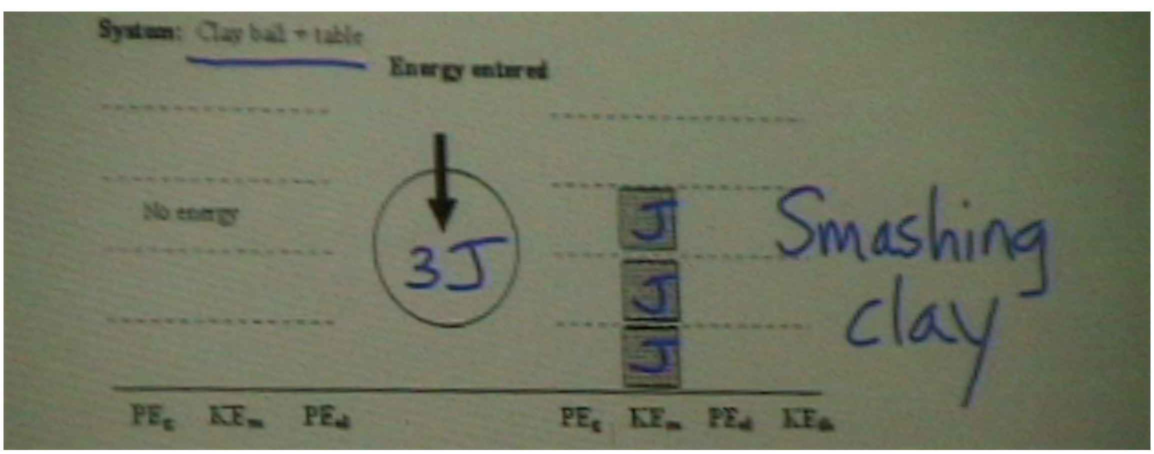

Figure 25. Bar chart in Allie's class.

She then told the class that in order to smash the clay, she would need to introduce energy to the system, so she represented this on the second bar chart with three bars. She then asked how much energy they introduced if each bar was one Joule (a unit of energy). The students responded "three Joules" so she drew an arrow pointing into the system circle and wrote "3J" in the center of the circle. Next, she worked on a second bar chart problem with the class, mostly through direct instruction and by asking a few questions (e.g., do I have any potential energy on this side?). During this time, Allie emphasized the difference between energy transfer and energy transformation. Next, she worked on two examples involving energy leaving the system. The following day, the students revisited their lab notebooks and added the ideas of work and bar charts.

PCK for bar charts. The analysis of Allie's interviews regarding the sequence of instruction summarized above resulted in a description of Allie's knowledge in terms of the five components of PCK.

Knowledge of curriculum. Allie introduced bar charts using scenarios and problems written on a worksheet. Describing those problems, Allie explains, "It is important to how the problem looks…you should list [key ideas] instead of embedding them in all those words where they're having to dig everything out." In this statement, Allie demonstrates her knowledge of the curricular resources, specifically that the problems and scenarios on the worksheets should be written so that they are accessible to students.

As a second example, Allie discussed the difference between pie charts and bar charts and indicated that they address different learning goals. She explains that bar charts address, "The idea of transfer and the idea of an open system," whereas pie charts address ideas of transformation within closed systems. In this example, Allie demonstrates her knowledge of how bar charts address the unit goals of energy transfer and open systems.

These examples, specifically, that problems and scenarios on the worksheets should be written so that they are accessible to students and that bar charts address the unit goals of energy transfer and open systems highlight Allie's knowledge of curriculum as connected to her use of bar charts. These specific examples are captured in the summary statements in the "Curriculum" box in Figure 26 at the end of this section.

Knowledge of instructional strategies. During her instruction on bar charts, Allie asked the students to represent the energy introduced into or out of the system using the symbol "J" for Joules. She told the students to think of each block of energy as one Joule. Allie explains, "I want them to associate energy with Joules." In this example, Allie demonstrates her knowledge of using a particular instructional strategy to help students build associations, specifically, that representing blocks as one joule each helps students associate energy with Joules.

As another example, Allie represented the system using a circle in the middle of two bar charts. She explains:

> The circle just gives a visual. It gives you some visual idea that energy is being transferred…It just gives them some idea that the energy is moving. You're doing work. You're moving something. You're moving the energy in or out.

In this example, Allie demonstrates her knowledge of using a certain strategy to help students understand ideas, specifically, that having the students represent the system using a circle helps them see the idea that energy is moving.

As a final example, Allie introduced bar charts as a representation for solving energy transfer problems, but she never discussed bar charts as representations for solving energy transformation problems. She explains:

> The one thing I did want to stay away from was saying, ‘Yeah, you can do transformations with bars,’ because you can, but I didn’t want to go there because I just wanted them to have that distinction in their head, just so that they didn’t get them muddied.

In this example, Allie demonstrates her knowledge of using a specific strategy to address a specific goal, namely, that she purposefully chose to use bar charts only for addressing ideas of energy transfer.

These examples, specifically, that representing blocks as one joule each helps students associate energy with joules, that representing the system using a circle helps students see the idea that energy is moving, and that using bar charts only for addressing ideas of energy transfer highlight Allie’s knowledge of instructional strategies as connected to her use of bar charts. These specific examples are captured in the summary statements in the “Instructional Strategies” box in Figure 26 at the end of this section.

Knowledge of student understanding. After introducing bar charts, Allie asked the students to write down the big ideas about work and bar charts in their lab notebooks. She explains, “I’ll have kids who are more linguistic who are going to look at that [lab notebook], and they’re going to remember that [ideas of work and bar charts] by reading their vocabulary.” In this example, Allie demonstrates her knowledge of student understanding in terms of different learning styles, specifically that linguistic learners will remember the ideas in bar charts better by reading them in their notebooks.

As another example, Allie discussed the transition from pie charts to bar charts in terms of students interest, explaining:

> It seems like a relief to them to go from pie to bar charts. It seems like all of a sudden it just kind of clears their head for a second and it puts them on a different path. You just hit this time with pie charts where you go, we've done enough of these because they're fried. You can feel it. So, you put them into bars and they seem to do better. It's still energy, but it's a different focus.

In this example, Allie demonstrates her knowledge of student interest and motivation in terms of bar charts, specifically, that transitioning to bar charts after pie charts is a relief for students because they see energy from a different perspective.

As a final example, Allie discussed her decision to use bar charts to only represent energy transfer and not energy transformation, explaining, "I just wanted them to have that distinction [pie charts for energy transformation and bar charts for energy transfer] in their head, just so that they didn't get them muddied, because they would at that point." In this example, Allie demonstrates her knowledge of student confusion, specifically, that using bar charts to represent energy transformation as well as energy transfer results in student confusion.

These examples, specifically, that linguistic learners will remember the ideas in bar charts better by reading them in their notebooks, that transitioning to bar charts after pie charts is a relief for students because they see energy from a different perspective, and that using bar charts to represent energy transformation as well as energy transfer results in student confusion highlight Allie's knowledge of student understanding as connected to her use of bar charts. These specific examples are captured in the summary statements in the "Student Understanding" box in Figure 26 at the end of this section.

Knowledge of assessment. During her instruction, Allie would use students' answers to bar chart questions on homework and quizzes to gauge their understandings. She discussed a specific example, explaining:

> This gave me a chance to see if I had gotten through with the open/closed system idea and the transfer idea. I had a few kids who missed that. They didn't understand when I talked in class about what's happening to the energy here. They didn't make that jump, so it really helped me. This question probably helped me the most to realize what I did on bar charts, I needed to go back and we need to practice a little bit more and do a few more. And just to give them another frame to look at, because this one actually helped me to figure out they understood that the energy was actually coming out of the system.

In this statement, Allie demonstrates her knowledge of assessment in terms of identifying student understandings and in terms of her assessment guiding her instruction, specifically that her students' answers on their homework revealed their misunderstandings about energy leaving the system and informed her decision to have the students practice a few more problems.

This example highlight Allie's knowledge of assessment as connected to her use of bar charts. This example is captured in the summary statement in the "Assessment" box in Figure 26 at the end of this section.

Orientations. In one of her earlier interviews, Allie indicated that she might try to introduce bar charts using marbles as she did with pie charts. She explains:

> I tried [teaching bar charts with marbles] with one of my [other] classes to see how they would react to it before I did it with first hour and it just didn't seem like something that they wanted to do…they were almost ready after a lot of exploring and a lot of talking and a lot them doing stuff, they were ready for me to just do some direct instruction…there are times when kids just really need that. They need to just get some information, and they need to get it in a way that is organized.

In this example, demonstrates two aspects of her orientation. First, she identifies her belief that the teacher's role is to provide students with information in an organized manner. Second, Allie reveals her belief that sometimes, students need direct instruction.

These examples, specifically, that the teacher's role is to provide students with information in an organized manner and that sometimes students need direct instruction highlight Allie's orientation as connected to her use of bar charts. These specific examples are captured in the summary statements in the "Orientations" box in Figure 26.

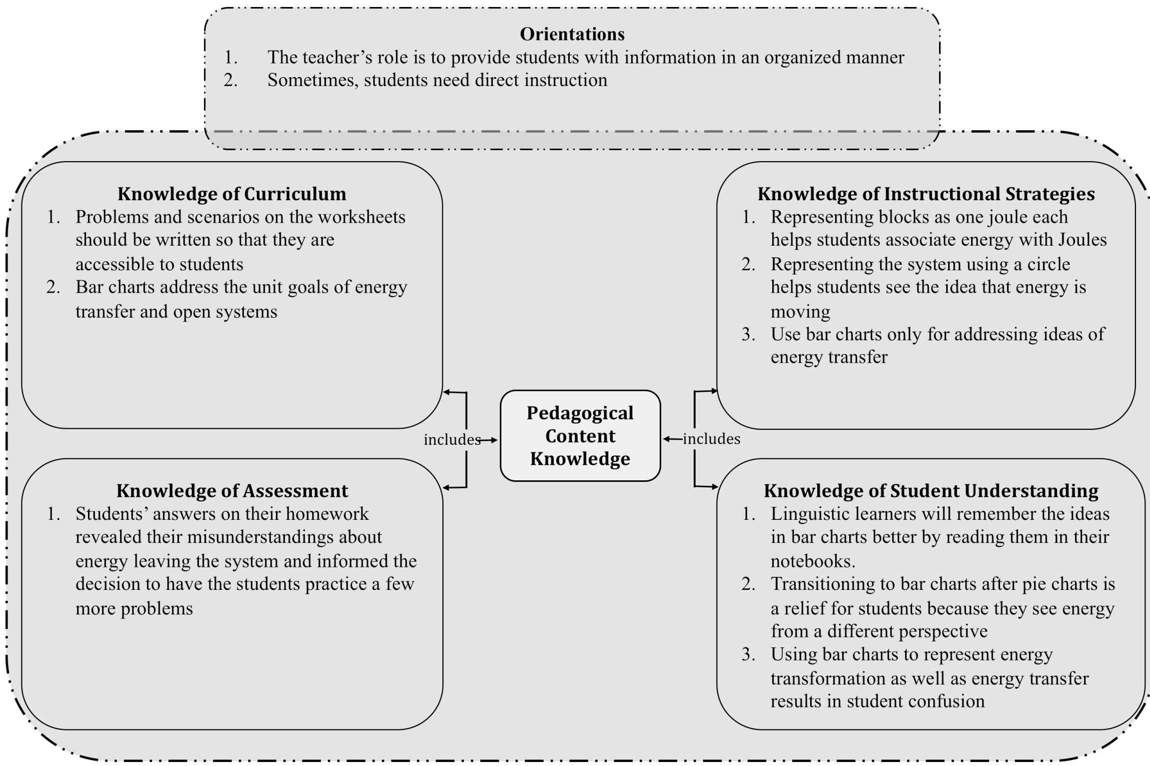

Figure 26. Examples of Allie's knowledge in all five components of PCK for bar charts.

Summary of PCK for bar charts. Viewed collectively, the five components reveal the interconnected nature of Allie's knowledge for using bar charts as a representation for teaching energy. For example, as captured in Figure 27, one component of Allie's orientation is the belief that the teacher's role is to provide students with information in an organized manner. This orientation is reflected in Allie's decision to organize her instruction so that bar charts are only for addressing ideas of energy transfer and based on her knowledge that using bar charts to represent energy transformation as well as energy transfer results in student confusion. However, Allie's decision to use bar charts in her instruction is based, in part, on her curricular knowledge that bar charts address the unit goals of energy transfer and open systems. Additionally, because of her orientation regarding organized instruction and her knowledge of using student homework to assesses student understanding, Allie is able to organize her instruction so that the students have enough practice solving bar chart problems prior to the end of the unit.

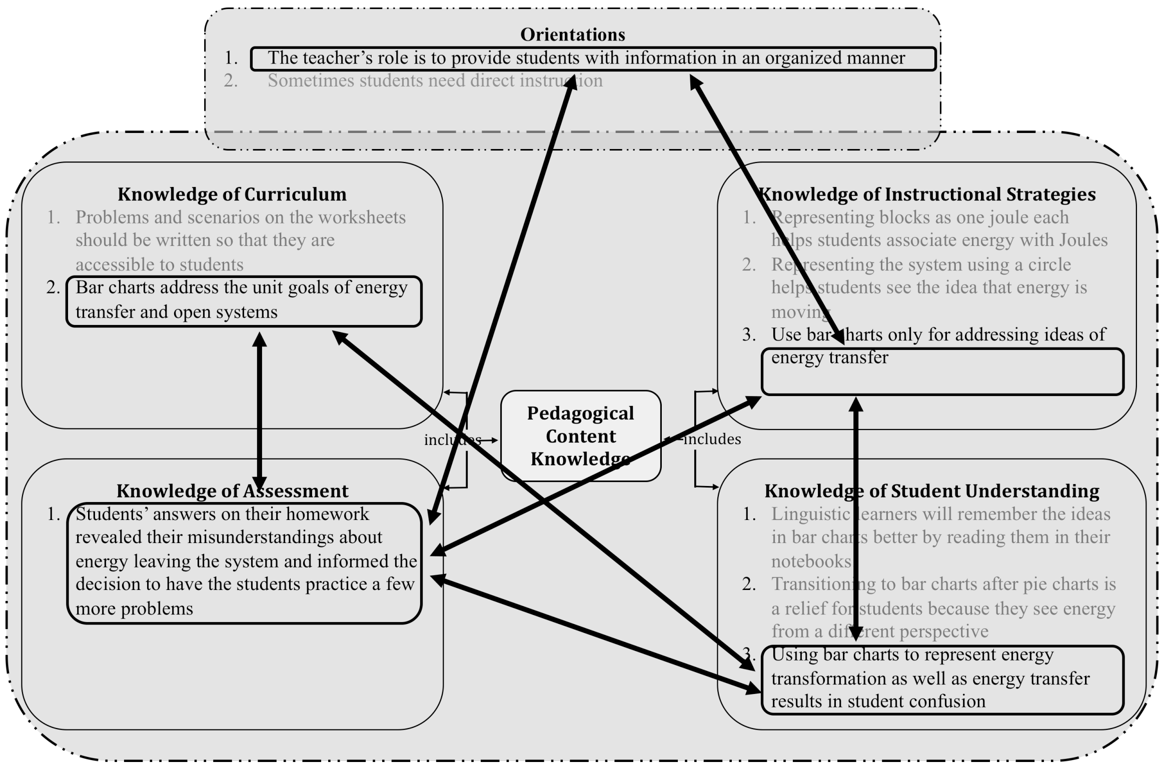

Figure 27. An example of the integrated nature of Allie's knowledge for using bar charts.

This description, and the corresponding figure, only captures a small slice of Allie's integrated knowledge for using bar charts to teach energy. Similar connections between the components of PCK are evident as a result of comparing Allie's instruction with the descriptions of her knowledge in all five components of PCK. However, these explicit connections are not described for the sake of space.

Assertions

The following question guided this phase of the analysis: What specialized knowledge do veteran teachers have for using representations to teach energy transformation and transfer? The following assertions addressing this question emerged from the analysis.

Assertion #1 – The participants have integrated knowledge for using representations to teach energy transformation and transfer. The summaries of PCK for each participant for the three central representations highlight the integrated nature of the knowledge that all three participants have for using representations to teach energy transformation and transfer. The participants' knowledge is integrated in that: 1) the participants' instruction is informed by all five components of PCK and 2) each of the components informs the other four components (to greater or lesser degrees). Although similar, these two claims differ subtly.

The central feature of the first claim is the emphasis on the integration between the participants' instructional decisions and the five components of PCK. Instead of making unilateral decisions based only on a single component of PCK, the participants drew from all five components during their instruction on the central representations. For example, a participant could have made the decision to use bar charts in their instruction based solely on the fact that bar charts were included in the Physics First curriculum. This decision would have been based on a single component of PCK, specifically, the participant's knowledge of curriculum. This decision could have been made regardless of the participant's knowledge of the other four PCK components. However, instead of making the decision to use bar charts only because they were in the curriculum, all three participants' use of bar charts was also based on their orientation, their knowledge of instructional strategies, their knowledge of assessment, and their knowledge of student understanding. All five of these components informed and shaped the participants' decisions and instruction on bar charts.

The first claim emphasizes how all five components of PCK inform instructional decisions, but it does not require that all of the components connect directly to each other. That is, an individual may draw upon his or her knowledge in all five components of PCK when teaching a topic, but the knowledge components may or may not be integrated. Therefore, the central feature of the second claim is the emphasis on how each component of PCK informs the other components. For example, Allie's orientation that students need to begin with basic ideas and her knowledge that some students need concrete representations (knowledge of student understanding) informed her decision to use marbles to introduce pie charts (knowledge of instructional strategies), her decision to introduce marbles before pie charts (knowledge of curriculum), and her decision to use marbles as a tool for assessing student understanding (knowledge of assessment). The PCK summaries described above highlight similar integrations of the participants' knowledge of all five components of PCK. In some cases, the integration occurs between all five components, while in other cases, the integration only occurs between a few of the components.

Assertion #2 – The participants understand the essential features of the representations. The descriptions and summaries of the participants' knowledge demonstrate that all three of the participants understood the basic and essential features of the central representations. For example, the participants deconstructed each of the central representations into their basic components and then introduced each representation one component at a time in a logical sequence. This required that the participants understand the essential features of the representation as well as how the essential features related to each other and the best way to introduce the features to the students. This understanding also prompted the participants to select certain representations (e.g. T-charts) instead of other representations (e.g. concept maps) based on the representation's specific features and how the features addressed the unit goals and facilitated student understanding.

The participants also used multiple representations to help the students understand and communicate their ideas about the same concept (i.e., pie charts and bar charts both address the Law of Conservation of Energy). This required that the participants understand how the different representations all connected to the same concept or idea. Because of their knowledge of the basic and essential features of the representations, the participants had the ability to modify specific features of the representations (e.g., system circle) in order to address their students' needs as well as to determine student difficulties.

Assertion #3 – The participants understand barriers to student learning regarding representations. The descriptions and summaries of the participants' knowledge demonstrate that all three of the participants understood a wide range of specific barriers to student learning regarding the central representations. For example, the participants recognized student misconceptions (e.g., energy is only electricity), understood student difficulties with objects at the stations (e.g., wind-up toy not understood as elastic energy), and were aware of student confusion tied to using abstract graphical representations (e.g., bar charts). In addition, the participants understood the difficulties that the students had with the instructional strategies that they used to introduce the representations (e.g., the system circle is sometimes confused with a pie chart), challenges that the students have with the curricular materials that supported the instruction (e.g., some of the problems are not accessible to students because of how they are written), and difficulties that the students have with the assessments used to determine student understandings (e.g., assessing terminology too early in the unit confuses students).

Assertion #4 – The participants know how to help students develop understandings about representations. The descriptions and summaries of the participants' knowledge demonstrate that all three of the participants understood how to help students develop understandings about the central representations. The participants drew from their knowledge in all five components of PCK in order to help the students develop these understandings. For example, the participants used a wide range of instructional strategies (e.g., modeling stations, T-Chart race, video clips, simulations, challenging homework prior to explanations, interactive analogies, etc) and a variety of assessments (e.g., ABC flash cards, logical questioning, whiteboarding, etc) during their instruction. These strategies and assessments were shaped by the participants' knowledge of student understanding (e.g., students have better understandings if they come up with definitions on their own, memorizing does not promote deep understanding, etc), their knowledge of the curriculum (e.g., T-charts, pie charts and bar charts all connect to the Law of Conservation of Energy, terms are important for future representations), and their orientations (e.g., come up with the terms first based on an exploration experience, begin with a common experience, break concepts down into basic components that build on each other, introduce one idea or component at a time). These five components of PCK functioned as an integrated group to inform how the participants helped the students develop understandings about the representations, and ultimately, about energy transformation and transfer.

Historical Approach to Energy Instruction

Throughout the interviews, I asked the participants to describe the differences between how they currently teach energy as opposed to how they taught energy "in the past" or "back then," and although the participants could have interpreted "in the past" to mean their instruction at any point in time prior to the instruction that I observed, all three of the participants frequently discussed their instruction primarily in terms of how they taught energy prior to Physics First and how they now teach energy after Physics First. Consequently, in the following section, I will use Physics First as the delineation between their past and present instruction because it surfaced as the most natural frame of reference. However, it is important to note that whereas the time period after Physics First captures the period from the start of the Physics First project to their observed instruction (2006-2010), the time period prior to physics first captures the period from their first teaching job to the start of Physics First (1984-2006, 1995-2006, and 1990-2006, respectively, for Jake, Findlay, and Allie).

Jake. Prior to Physics First, Jake's instruction on energy was guided by the curricular goals of students being able to describe energy transformations, state the Law of Conservation of Energy, and calculate work and energy transfers. In short, the goals guiding Jake's instruction prior to Physics First were similar to his current goals, although the emphases and the sources of the goals were different. For example, Jake explained that he focused primarily on energy transformation because of the district textbook that he was using at the time. The textbook also served to determine the types and forms of energy that were discussed as well as the types of transformations that were investigated. Jake explains:

> We'd take a look at defining the different forms of energy and our definitions, or our types of energy were different. For example, I know that in the old days, we had four types of potential energy and five types of kinetic energy. And now, through Physics First, we've broken that up into two or three basic types of potential energy and like two or three basic types of kinetic energy.

Because the focus of the unit was on simple energy transformations, the focus of his specific instructional strategies was different. For example, Jake began his current instruction by having the students investigate the energy transformations at a variety of stations. After exploring the stations, the students shared their ideas as a class and constructed understandings about the types and forms of energy. But historically, instead of starting with a variety of stations and building understandings as a class, Jake began with a single object and asked the questions, "What kind of energy is in this object" and "What does this object convert energy into and from what form to what form?" This pattern of starting with a single object and asking questions about its type of energy and its transformation necessitated that he provide the students with vocabulary and explanations about the types and forms of energy prior to investigating the objects.

Additionally, because the goal of the unit was primarily on energy transformation, the objects that the class explored were different. Jake explains:

> Some of them were things like plants. We'd even put things like apples, because back then it wasn't so much that we were looking at systems, we weren't necessarily looking at initial states and final states, just energy

> conversions. Like if you take a bite of an apple, how is the energy converted from the apple? If you have a plant, how does the plant convert sunlight into chemical energy?

He concludes, “So for us, the energy was slightly different. It was more about the conversion of energy” and not as much about the Law of Conservation of Energy.

Because the focus was on energy transformation, the purposes behind the representations that Jake used to communicate concepts about energy were different. For example, in the current unit, Jake used a T-chart to represent the types and forms of energy, although historically, he used a concept map type of representation to organize the types and forms of energy. And although the concept map was similar to the T-chart, its purpose was different. Although the concept map was designed as a tool to help the students identify energy transformations, Jake also explained that, “The concept map was more complex. It had much more branching.” In contrast, he explained that the T-chart was more simplistic and reflected his goal of “Making sure that I got to gravitational, kinetic, elastic, all those things that are in the pie charts and the bar graphs because those are where the keys were.” So whereas the concept map was used solely for energy transformations, the T-chart was used to lay the foundation for energy transformations and transfers using pie charts and bar charts.

Jake also did not use pie charts or bar charts to represent energy transformations prior to Physics First. Jake explains:

> We always did energy conversions but we never talked about how much energy we had [using pie charts or bar charts]. What we had to do before was we had to actually mathematically calculate how much energy we had at the beginning, how much at the end, and how the energy changed. And then you’d come up with the idea that the total amount of energy is still there.

This stands in contrast to Jake's current approach of using pie charts and bar charts to qualitatively introduce and reinforce the Law of Conservation of Energy.

Jake also used homework for different purposes early in his teaching. Primarily, the purpose of homework was to give students practice solving energy transformation problems. Additionally, Jake explains, "Homework was strictly turn it in, I grade it, I pass it back." This stands in contrast to his current use of homework to have students wrestle with ideas (e.g., ground level) prior to coming to class so that they are prepared for discussion and his use of simple assessments (e.g., holding up fingers) to gauge student understanding.

Because the focus of Jake's instruction prior to Physics First was primarily on energy transformations, he spent very little time on the concept of work and energy transfer. Consequently, many of the ideas and concepts in his current instruction were irrelevant in the past. He explains, "We never identified work in or work out…we didn't care about the environment. We didn't care if it was an isolated or non-isolated system…it wasn't tested, it wasn't assessed. Nobody talked about it." So, whereas in his current instruction Jake spent time exploring work conceptually, in his previous instruction, he focused on simply calculating work.

Jake also explained that historically, he was unaware of student misconceptions about energy. Therefore, he did not plan his instruction or select strategies with students' ideas in mind (e.g. specific examples to address common misconceptions), and consequently, he did not break concepts down into basic components or introduce concepts one component at a time.

After his introduction to the Physics First curriculum, Jake started incorporating many of the things he currently uses into his instruction, including T-charts, pie charts, and bar charts. However, during the first year of teaching from the Physics First curriculum, Jake did not perceive that identifying systems was important. He explains, “Back then we thought what does it matter if you circle a system or not circle a system.” Therefore, instead of using a dashed circle to identify the system, he did not circle systems at all. Additionally, Jake did not use the system circle with bar charts as he does currently. He explains:

> The little circle that you put between the two bar charts…they never really said what that circle was for – just that the circle was considered the system and the arrows that go in are work that goes into the system and arrows that go out are work that goes out of the system.

This stands in contrast to how he now has his students draw objects inside and outside of the system circle and how the work arrow is drawn using blocks that correspond to the blocks in the bar charts (see Figure 19).

Finally, in the first year using the Physics First curriculum, Jake did not break down the concepts into the same component pieces or sequence concepts as he does now. He explains, “It was really hard for us to identify when do you throw out these new terms as well as what could make this easier for the students to understand.” Because he did not introduce the concepts one idea at a time, he had a difficult time identifying exactly what ideas were causing the students difficulties.

Findlay. Like Jake, prior to Physics First, Findlay’s instruction on energy was guided by the curricular goals of students being able to describe energy transformations, state the Law of Conservation of Energy, and calculate work and energy transfers. And like Jake, although the goals guiding Findlay’s instruction prior to Physics First were similar to her current goals, the emphases of the goals were different. Consequently, the difference in the emphases of the unit goals informed Findlay's instructional strategies. For example, early in her career, Findlay did not begin the unit by giving her students a common experience from which they could build understanding through questioning and through a logical sequence of ideas. Instead, Findlay focused on helping the students simply memorize the types and forms of energy.

Prior to Physics First, Findlay did use stations in her instruction. However, Findlay did not ask the students to identify states and systems, but instead just asked the students to describe what was happening in the beginning and what was happening at the end of a given scenario. She explains:

> When I used to teach this before, I didn't [have the students identify states and systems] because it just seemed like almost a silly step. I was like, 'What do you start out with? What do you end up with?' and that sort of thing.

This stands in contrast to her current strategies of identifying states and systems in writing and with system boxes (see Figure 22) so that the students can consider scenarios from multiple perspectives. In addition, Findlay was unaware that some of the objects at the stations caused student confusion.

Prior to Physics First, Findlay also explains, "Everything was treated kind of like a black box – energy in, energy out…we didn't have any pie charts, we didn't have any bar charts we didn't have any of that kind of physics feel." This stands in contrast to Findlay's current instruction, which focuses on pie charts and bar charts as representations of energy transfer and transformation. And because she took a more basic approach to teaching energy, she did not have to focus on breaking concepts down into basic components that build on each other (e.g., interactive analogies, example problems that build on each other, etc) or on assessing student understanding of the basic components along the way (e.g., ABC cards, symbols written in pie charts, etc) or as a means of promoting student thinking.

Like Jake, Findlay also used an energy concept map instead of a T-chart to represent the types and forms of energy. She explains, "They would have like chemical energy, and it is connected to potential. And then there would be maybe some examples of what potential chemical energy might be, like food, gasoline, or whatever." Because she did not incorporate pie charts or bar charts, the purpose of the concept map was solely tied to being able to identify and name the types of energy and the energy transformations. Additionally, because the emphasis was on simple energy transformations, Findlay explains that prior to Physics First, "It was a different kind of learning…there was no theme, there was no recurring concept or recurring thinking pattern or anything like that." Instead, she describes the learning as a "memorize and go kind of thing and not something building on a concept that broadens." She explained that the students learned how to calculate work, power, gravitational energy, and kinetic energy but that they did not see the underlying connections between the ideas.

Another element of Findlay's current instruction is providing opportunities for students to see concepts from multiple angles, including demonstrations, presentations, and exploration activities as well as pie charts and bar charts. But, Findlay discussed that in the past she did not provide students with as many different experiences with the same concept. She explains, "That comes over time. You find more and more things that fit."

After her introduction to the Physics First curriculum, Findlay started incorporating many of the things that she currently uses into her instruction, including T-charts, pie charts, and bar charts. However, during the first year of teaching from the Physics First curriculum, Findlay described that her students had difficulties and misunderstandings about pie charts. She explains, "I would have them at pie charts from the beginning, thinking well it's all connected, and it's not a hard thing." This stands in contrast to her current approach of purposefully selecting strategies to address student misunderstandings such as breaking down concepts into basic components and then introducing those components in a logical sequence.

Findlay also did not emphasize the connection between pie charts, bar charts, and the Law of Conservation of Energy during her first year of teaching from the Physics First curriculum. She explains, "I remember that the first year we did the energy unit I found that kids were not making that connection…I just found that I needed to keep that idea from the beginning." This strategy of emphasizing the Law of Conservation of Energy is evident throughout Findlay's current instruction.

Allie. Like Jake and Findlay, prior to Physics First, Allie's instruction on energy was guided by the curricular goals of students being able to describe energy transformations, state the Law of Conservation of Energy, and calculate work and energy transfers. And like Jake and Findlay, the difference in the emphases of the unit goals informed Allie's instructional strategies. For example, instead of introducing energy concepts by having students consider their own experiences with energy (e.g., roller coasters) and wrestle with their ideas, Allie explained that she "Defined everything and then expected them to remember it."

One of the primary differences between Allie's current instruction and her instruction prior to Physics First is that in the past, the focus of the first half of the unit was on preparing students to build Rube Goldberg machines designed to show energy transformations. Because the focus was on preparing students for Rube Goldberg machines, Allie explains that in the beginning of the unit she, "Taught them all of the background, then they designed, and then they built." She explained that they spent two weeks or more building the Rube Goldberg machines.

Because the focus of the unit was on energy transformation and ultimately building Rube Goldberg machines, Allie did not use graphical representations like pie charts and bar charts prior to Physics First. She explains, "Representing energy graphically was a completely new idea for this physics." Instead, Allie used a concept map type of representation to organize the types and forms of energy. But instead of asking the students to help her construct the concept map like she currently does with the T-chart, she just provided the students with the concept map and showed them how to use it. Additionally, Allie did not represent complex ideas using the same types of interactive analogies, simulations, or animations that she currently uses. She explains, "We used animations but they weren't as good as these. They were shorter or they didn't have as many nice applications. You couldn't just mold them to what you wanted."

In her current instruction, Allie encourages the students to share their experiences and to justify their ideas and thinking, both through discussion and by using the whiteboards. But prior to Physics First, Allie did not focus on having the students share their ideas as a class or build understandings together.

After her introduction to the Physics First curriculum, Allie started incorporating many of the things that she currently uses into her instruction, including T-charts, pie charts, and bar charts. However, during the first year of teaching from the Physics First curriculum, Allie explains she would begin with the stations objects and then ask:

> What forms of energy are here? What forms of energy are possible for this toy or whatever? And the kids would list out you know, and then I'd do one with them on the board or I would say okay, we're starting off with 100% of potential elastic energy. And then we would just kind of move from there. And then we just started drawing the pie pieces. And they didn't really have any ownership of thinking about it. They just kind of went with me and then when I tried to get them to do it on their own they were confused. A lot of them were confused. Like they never really digested why they were doing.

This strategy of introducing pie charts immediately after introducing the energy types and forms stands in contrast to Allie's current approach of providing the students with multiple experiences and opportunities to explore the types and forms of energy.

During the first year teaching from the Physics First curriculum, Allie explained that she used the curriculum questions exactly as they were written, but found that "the questions were really too abstract and the kids were blown away by them." Consequently, many of the problems and questions that she uses currently have been modified from the original curriculum materials. In addition, during her first couple of years teaching from the Physics First curriculum, Allie did not use marbles to introduce pie charts, but instead transitioned directly from indentifying energy types and forms to drawing pie charts.

Change in Knowledge

The purpose of the second phase of the analysis of teacher knowledge was to identify how each participant historically used representations so that comparisons could be made between their current knowledge of using representations to teach energy and their previous knowledge. This phase of the analysis was guided by the question: How does knowledge change over the teacher's career? The analysis revealed that the participants developed more sophisticated knowledge for using representations relative to all five components of PCK and that their knowledge became more integrated. These findings are described below in terms of the five components of PCK.

Changes in orientations. In the analysis of the participants' current knowledge for using representations to teach energy transformation and transfer, the participants demonstrated orientations relative to a variety of the orientations characteristics described in the analysis, including their beliefs about the teacher's role in learning science, their beliefs about the student's role in learning science, and their beliefs about student learning. For example, the participants believed that the teacher's role included guiding students towards understandings, breaking concepts down into basic components so that they can be reconstructed throughout the unit, and providing multiple representations from which students can develop understandings about concepts and ideas. Regarding the student's role, the participants believed that students should begin instruction by engaging in common experiences. In terms of student learning, the participants believed that students learn by building or constructing ideas as a class.

These orientations, however, were not reflected in the participants' memories of their historical instruction on energy as described above. Instead, the participants' orientations regarding the role of the teacher, in general, were characterized by the teacher doing more direct instruction (versus guided instruction), presenting ideas in larger chunks (versus breaking ideas down into basic components), and providing fewer representations of concepts (versus providing multiple representations). The participants' orientations regarding the role of the student were characterized, in general, by the students having individual experiences (versus common experiences) and the participants' beliefs about student learning were characterized by students passively receiving ideas (versus building ideas as a class). These differences are highlighted in Table 4.

Table 4

Examples of the Participants' Changes in Orientations from Their Previous to Their Current Instruction.

Characteristic of Orientation	Examples of Changes in Orientation		
	Previous Instruction		*Current Instruction*
Role of teacher	Provide direct instruction	→	Provide guided instruction
Role of teacher	Present ideas in larger chunks	→	Break ideas into basic components
Role of teacher	Provide fewer representations	→	Provide multiple representations
Role of student	Have individual experiences	→	Engage in common experiences
Student learning	Passively receive ideas	→	Build ideas as a class

Changes in knowledge of curriculum. In the analysis of the participants' current knowledge for using representations to teach energy transformation and transfer, the participants demonstrated their knowledge of curriculum relative to a variety of the knowledge of curriculum characteristics described in the analysis, including their knowledge about the goals of the curriculum, knowledge of the longitudinal curriculum, knowledge of modifying curricular materials, and knowledge of the relationships between ideas and concepts. For example, regarding their knowledge of the curricular goals, the participants revealed that they placed an emphasis on a variety of concepts related to energy (e.g., energy transformation, energy transfer, Law of Conservation of energy, work, etc) and that the goals of the unit were deeper than simple memorization of ideas (e.g., identification, conceptual understanding, relationships, etc). In terms of their knowledge of the longitudinal curriculum, the participants demonstrated knowledge of using representations to inform future representations and concepts within the unit (e.g., T-chart prepares students for pie charts and bar charts). Finally, in their current instruction, the participants demonstrated their knowledge of modifying curricular materials (e.g., redrawing scenarios) and their knowledge of emphasizing the relationship between ideas (e.g., pie charts connect concepts of energy transformation and the Law of Conservation of Energy).

These characteristics of the participants' curricular knowledge, however, were not reflected in the participants' memories of their historical instruction on energy as described above. Instead, the participants' knowledge of the curricular goals was characterized, in general, by emphasizing a fewer number of concepts (e.g. the emphasis was only on energy transformation although the goals included the Law of Conservation, energy transfers, and work) and by focusing on shallower learning goals (e.g., memorization and calculation). In terms of their knowledge of the longitudinal curriculum, the participants only used a single representation to inform a single concept (e.g., concept map for transformation, equations for work). Finally, the participants used the curricular materials and resources as written (instead of modifying them to their context) and they did not emphasize the connections between representations or concepts.

These differences between the participants' current instruction and their past instruction are highlighted in Table 5.

Table 5

Examples of the Participants' Changes in Knowledge of Curriculum from Their Previous to Their Current Instruction

Characteristic of Curriculum	**Examples of Changes in Knowledge of Curriculum**		
	Previous Instruction		*Current Instruction*
Goals of curriculum	Emphasis on fewer concepts	→	Emphasis on greater number of concepts
Goals of curriculum	Shallower learning goals	→	Deeper learning goals
Longitudinal curriculum	Representations inform single concept	→	Representations inform multiple concepts
Modifying materials	Used materials as written	→	Modified curricular materials
Relationships between ideas	Did not emphasize connections	→	Emphasized connections between representations

Changes in knowledge of instructional strategies. In the analysis of the participants' current knowledge for using representations to teach energy transformation and transfer, the participants demonstrated their knowledge of instructional strategies relative to a variety of the knowledge of instructional strategy characteristics described in the analysis, including, their knowledge of using specific strategies in specific ways and for specific reasons, their knowledge of sequencing strategies, and their knowledge of using specific strategies to facilitate student learning. For example, in terms of using specific strategies in specific ways and for specific reasons, the participants used interactive strategies to build complex ideas (e.g., *Family Guy* analogy, building pie charts on the SMART Board, etc) and selected specific strategies to address student misunderstandings (break ideas down into basic components, use specific examples to address common misconceptions, etc). Regarding their knowledge of sequencing instructional strategies, the participants introduced vocabulary after the students had an experience and they sequenced their instructional strategies to promote the construction of ideas (e.g., students completed the exploration lab and then generated names for the forms of energy). In terms of using instructional strategies to facilitate student learning, the participants connected examples to the students' experiences and used homework to for assessment but also to promote student thinking before coming to class.

These characteristics of the participants' knowledge of instructional strategies, however, were not reflected in the participants' memories of their historical instruction on energy as described above. Instead, the participants' used direct instruction to address complex ideas (versus interactive strategies), and did not select specific strategies to address student misunderstanding. Furthermore, the participants introduced vocabulary before engaging students in experiences and sequenced instructional strategies for direct instruction (versus sequencing strategies to promote the construction of ideas). Finally, in their past instruction, the participants used examples that were less connected to the students' experiences and only used homework for assessing students (versus for also promoting student thinking). These differences between the participants' current instruction and their past instruction are highlighted in Table 6.

Table 6

Examples of the Participants' Changes in Knowledge of Instructional Strategies from Their Previous to Their Current Instruction

Characteristics of Instructional Strategies	**Examples of Changes in Knowledge of Instructional Strategies**		
	Previous Instruction		*Current Instruction*
Specific reason for using representation	Used direct instruction to address complex ideas	→	Used interactive strategies to build complex ideas
Specific reason for using representation	Did not select strategies to address student misunderstanding	→	Select strategy to addresses student misunderstanding
Sequence	Introduce vocabulary before an experience	→	Introduce vocabulary after an experience
Sequence	Sequence strategies for direct instruction	→	Sequence strategies to promote construction of ideas
Facilitates student learning	Examples less tied to student experiences	→	Examples tied to student experiences
Facilitates student learning	Homework just for assessing students	→	Homework also promotes student thinking

Changes in knowledge of student understanding. In the analysis of the participants' current knowledge for using representations to teach energy transformation and transfer, the participants demonstrated their knowledge of student understanding relative to a variety of the knowledge of student understanding characteristics described in the analysis, including their knowledge of student misconceptions, student motivators, student difficulties, student learning styles, and student confusion. For example, the participants recognized specific student misconceptions (e.g., energy is only electricity), were aware of student motivators (e.g., T-chart competition), had knowledge of specific student difficulties (e.g. connecting concrete experiences to abstract representations), had understandings of student learning styles (e.g., exploration labs, discussions, using manipulatable objects like marbles), and had knowledge of specific student confusion (e.g., about objects used for lab activity, pie charts same as system circle).

These characteristics of the participants' knowledge of student understanding, however, were not reflected to the same extent in the participants' memories of their historical instruction on energy as described above. Instead, the participants discussed having weaker knowledge of specific student misconceptions, less awareness of student motivators, weaker knowledge of specific student difficulties, limited understandings of learning styles, and weaker knowledge of specific student confusion. These differences between the participants' current instruction and their past instruction are highlighted in Table 7.

Table 7

Examples of the Participants' Changes in Knowledge of Student Understanding from Their Previous to Their Current Instruction

Characteristics of Student Understanding	**Examples of Changes in Knowledge of Student Understanding**		
	Previous Instruction		*Current Instruction*
Misconceptions	Weaker knowledge of specific student misconceptions	→	Stronger knowledge of specific student misconceptions
Motivators	Less awareness of student motivators	→	Greater awareness of student motivators
Difficulties	Weaker knowledge of specific student difficulties	→	Stronger knowledge of specific student difficulties
Learning styles	Limited understandings of learning styles	→	Better understandings of learning styles
Confusion	Weaker knowledge of specific student confusion	→	Stronger knowledge of specific student confusion

Changes in knowledge of assessment. In the analysis of the participants' current knowledge for using representations to teach energy transformation and transfer, the participants demonstrated their knowledge of assessment relative to a variety of the knowledge of assessment characteristics described in the analysis, including their knowledge of when to assess and their knowledge of strategies for assessment. For example, the participants demonstrated knowledge of using assessments to reveal student understanding during instruction as well as multiple strategies for doing so (e.g., ABC flash cards, holding fingers up). The participants also demonstrated knowledge of using representations to assess students (e.g., what students write in the pie chart circles), knowledge of emphasizing student justification in order to reveal student thinking (e.g., discussions, whiteboarding), and knowledge of breaking concepts into basic ideas in order to identify specific student misunderstandings.

These characteristics of the participants' knowledge of assessment, however, were not reflected to the same extent in the participants' memories of their historical instruction on energy as described above. For example, the participants only discussed assessing students after instruction. Furthermore, representations were not used to assess student understanding, less emphasis was placed on student justification, and the participants did not assess student understanding by breaking concepts down into basic ideas. These differences between the participants' current instruction and their past instruction are highlighted in Table 8.

Table 8

Examples of the Participants' Changes in Knowledge of Assessment from Their Previous to Their Current Instruction

Characteristics of Assessment	**Examples of Changes in Knowledge of Assessment**		
	Previous Instruction		*Current Instruction*
When to assess	Assess after instruction	→	Assess during and after instruction
Strategy for assessment	Representations not used to assess students	→	Representations used to assess students
Strategy for assessment	Less emphasis on student justification	→	Greater emphasis on student justification
Strategy for assessment	Leave concepts as big ideas	→	Break concepts into basic ideas

Assertions

The following question guided this phase of the analysis: How does knowledge change over the teacher's career? The following assertions addressing this question emerged from the analysis.

Assertion #1 – The participants developed more integrated knowledge for using representations to teach energy transformation and transfer. Taken as a whole, the descriptions of the participants' memories of their previous knowledge for using representations to teach energy transformation and transfer as compared to their current knowledge reveal that the participants developed more integrated knowledge for using representations. The comparison reveals that in their previous instruction, the individual knowledge components did not inform the other components to the same degree that they did in the participants' current instruction. That is, in their current instruction, the participants drew from all five components when planning and implementing instruction, whereas in their previous instruction, the participants' instruction was guided by knowledge of just a few components. For example, in the participants' previous instruction on energy, the instructional strategy of the teacher defining terms in the beginning of the unit was not selected based on its effectiveness at addressing student misunderstandings or its utility in assessing student understanding, but instead because defining terms was connected to the goals of memorizing the types and forms of energy. This stands in contrast to the participants' current instructional strategy of introducing terminology based on the students' experiences so that misconceptions and confusion can be identified along the way and so that the students will be able to do more than just memorize the terms. This example typifies the less integrated nature of the participants' previous knowledge compared to their more integrated current knowledge for using representations.

Assertion #2 – The participants developed understandings of the essential features of specific representations for teaching energy. The descriptions of the participants' previous knowledge for using representations to teach energy transformation and transfer as compared to their current knowledge reveal that the participants developed understandings of the essential features of specific representations for teaching energy over time. For example, in their current instruction, the participants demonstrated an understanding of the basic and essential features of the central representations, including knowledge of deconstructing each of the central representations into their basic components and then introducing each representation one component at a time in a logical sequence so that students could construct understandings. However, in their previous instruction, the participants presented the big ideas in larger chunks (versus basic components) using fewer representations (e.g. concept maps and equations). Additionally, the participants did not reveal any knowledge of breaking the representations down into basic components or of purposefully sequencing or integrating the essential features of the representations throughout the unit.

In their current instruction, the participants also used multiple representations to help the students understand and communicate their ideas about the same concept (e.g., pie charts and bar charts both address the Law of Conservation of Energy). This required that the participants understand how the different representations all connected to the same concept or idea. However, in their previous instruction, the participants used isolated and single representations to help the students understand different concepts (e.g., concept maps addressed energy transformation while equations addressed energy conservation). Using single representations for single concepts did not require that the participants understand the essential features of the representations or how those features were connected to each other.

Assertion #3 – The participants developed understandings of barriers to student learning regarding specific representations. The descriptions of the participants' previous knowledge for using representations to teach energy transformation and transfer as compared to their current knowledge reveal that the participants developed understandings of barriers to student learning regarding specific representations. For example, in their current instruction, the participants recognized student misconceptions (e.g., energy is only electricity), understood student confusion with objects at the stations (e.g., wind-up toy not understood as elastic energy), and were aware of student difficulties tied to using abstract graphical representations (e.g., bar charts). However, in their previous instruction, the participants were less aware of student misconceptions regarding specific representations and less aware of student confusion and difficulties connected to representations.

Additionally, in their current instruction, the participants understood the confusion that the students have with the instructional strategies that they used to introduce the representations (e.g., the system circle is sometimes confused with a pie chart), challenges that the students have with the curricular materials that supported the instruction (e.g., some of the problems are not accessible to students because of how they are written), and confusion that the students have with the assessments used to determine student understandings (e.g., assessing terminology too early in the unit confuses students). However, in their previous instruction, the participants used strategies that did not address student difficulties in terms of constructing knowledge (e.g., provided terminology through direct instruction), did not address student difficulties developing big ideas (e.g., little emphasis on recurring concepts), and the participants did not use representations to reveal the difficulties that students were having.

Assertion #4 – The participants developed knowledge of how to help students develop understandings about representations. The descriptions of the participants' previous knowledge for using representations to teach energy transformation and transfer as compared to their current knowledge reveal that the participants developed knowledge of how to help students develop understandings about representations. For example, in their current instruction, the participants used a wide range of instructional strategies and a variety of assessments during their instruction. These strategies and assessments were shaped by the participants' knowledge of student understanding, their knowledge of the curriculum, and their orientations. The five components of PCK functioned as an integrated group to inform how the participants helped the students develop understandings about the representations, and ultimately, about energy transformation and transfer. However, in their previous instruction, the participants' PCK components did not function collectively to facilitate student understanding. For example, the participants used examples to support student learning that were disconnected from the students' experiences and used instructional strategies independent of the students' misconceptions or challenges. In addition, the participants did not use representations for assessment during instruction, presented big ideas all at once, and did not provide the students with multiple representations for understanding energy concepts and different points throughout the instruction. Ultimately, in their previous instruction, the five components of PCK did not function as an integrated group to inform how the participants used representations to help their students develop understandings about energy transformation and transfer.

Variation in Experiences

The analysis of the variation in the participants' experiences was guided by the question: What experiences influence change in teacher knowledge? I will describe the findings in terms of: 1) the experiences and sources corresponding to the participants' instruction focused on the central representations, 2) the experiences and sources corresponding to the participants' instruction for the entire energy unit, and 3) descriptions of the experiences and sources corresponding to the participants' instruction for the entire unit.

Experiences Corresponding to the Central Representations

The analysis of the experiences and sources corresponding to the participants' instruction focused on the central representations resulted in the identification of nine categories of experiences and sources that corresponded to the participants' development of knowledge for using the three central representations to teach the topic of energy. The nine categories are: 1) teaching experience, 2) Physics First, 3) other school district-supported professional development 4) collaboration with current colleagues, 5) past collaboration with experienced teachers, 6) academic experiences as a learner of science, 7) school district expectations, 8) collaboration with university faculty and other university professional development, and 9) non-academic life experiences. These nine categories of experiences and sources make up the phenomenographic outcome space.

The participants' descriptions and explanations that served as the basis for the outcome space are described below.

Teaching experience. During the sections of the interviews focused on the instruction related to the three central representations, the participants identified their prior teaching experience as a source informing their knowledge for teaching. For example, describing the experiences that informed his knowledge of the misconceptions that students have about energy, Jake explained:

> The older you are, the more that you teach, the more you already know what kinds of questions the kids are going to ask. And I can be more prepared. I also have a pretty good idea as to where they're going to have misconceptions. Cause every year we go over misconceptions and what do you know about electricity. What can you tell me? And then I find out and we just kind of move from there.

In this statement, Jake describes how his experiences teaching energy informed the development of his knowledge of student misconceptions and difficulties; knowledge which was highlighted previously in Jake's PCK for using T-charts/vocabulary (e.g., energy is only electricity) (see Figure 7), pie charts (e.g., how objects falls) (see Figure 14), and bar charts (e.g., identifying systems is difficult for students) (see Figure 20).

Describing her knowledge that students are sometimes confused by certain station objects, Findlay explains:

> Over time I've started figuring that out – that kids are having trouble with the elastic one when it comes to springs – because they don't always see the springs, or for windup things, or they don't know that there's a spring in there…I'm having them write about it in their lab book, so I'm discovering those things.

In this statement, Findlay reveals how her teaching experience informed her knowledge of student confusion regarding the objects selected for the stations;

knowledge of student understanding which was highlighted previously in Findlay's PCK for using T-charts/vocabulary (see Figure 10).

As another example, explaining the source of her knowledge for redrawing a pendulum scenario on a worksheet, Findlay states:

> "I found that in future things that I gave them, like on a quiz or whatever, they would think everything between here [at the top position of the pendulum] and there [at the bottom position of the pendulum] needs to be half-half [half kinetic energy and half potential energy].

In this example, Findlay shows how her teaching experience informed her knowledge of redrawing scenarios; knowledge of modifying curricular materials which was highlighted previously in Findlay's PCK for using pie charts (e.g., redrawing the pie chart pendulum scenario) (see Figure 15) and bar charts (e.g., changing the system circle to a system box) (see Figure 23).

Describing the source of her knowledge of engaging students in ideas about energy prior to introducing terminology, Allie explains:

> I just think it came down to finally getting the fact that you left kids behind sometimes and you didn't even realize it. You kind of just took off and you had no clue that where they were. You thought they got it but when you went back and really dug deeper and said what does that mean?

In this statement, Allie articulates how her teaching experience informed her decision to introduce ideas before terminology; knowledge of sequencing instructional strategies which was highlighted previously in Allie's PCK for using T-charts/vocabulary (e.g., watch and discuss roller coaster video and explore energy ideas prior to introducing terminology) (see Figure 11).

As a final example, Allie described how her teaching experience informed her knowledge of building from basic ideas to more complex ideas. She explains that building from basic to more complex ideas "Didn't completely make sense until I saw kids go through it and react to it. And then I said, 'Oh!'" In this example, Allie reveals how her teaching experience played a role in informing her belief that students need to begin with basic ideas first; an aspect of Allie's orientation which was highlighted previously in her PCK for using pie charts (e.g., build pie charts with marbles before drawing pie charts) (see Figure 17).

These examples highlight the types of teaching experiences that informed the development of the participants' knowledge for using the central representations to teach the topics of energy transformation and transfer. Specifically, the participants' teaching experiences informed their knowledge of student misconceptions and difficulties (see Table 7), knowledge of student confusion (see Table 7), knowledge of modifying curricular materials (see Table 5), knowledge of sequencing instructional strategies (see Table 6), and their belief that students need to begin with basic ideas first (see Table 4). These examples capture the participants' experiences teaching junior high science throughout their careers, including their interactions with students, their use of instructional strategies, their interactions with the curriculum, and their utilization of assessments while teaching multiple subjects and topics. The specific characteristics of these experiences (as well as the characteristics of the remaining experiences and sources in the outcome space) will be described later in the findings.

Physics First. During the sections of the interviews focused on the instruction related to the three central representations, the participants also identified Physics First as a source informing their knowledge for teaching. For example, describing the experiences that informed his knowledge of using pie charts the connect the concepts of energy transformation and the Law of Conservation of Energy, Jake explains:

> So [pie charts] really, in my opinion, just makes it really easy to go into the Law of Conservation of Energy because you always have 100%. Which means what you start with is what you finish with…I think that Physics First was probably the way that opened my eyes more than any.

In this example, Jake reveals how Physics First informed his knowledge of using pie charts to connect energy transformation to the Law of Conservation of Energy; curricular knowledge of the relationship between ideas within the unit which was highlighted previously in Jake's PCK for using pie charts (see Figure 14) and bar charts (e.g., systems were introduced early in the unit so students were prepared for bar charts) (see Figure 20).

As another example, Jake described the source that informed his knowledge of introducing ideas one component at a time, explaining:

> I feel like [an instructor at the Physics First summer academy] was the one that really got me into doing that, because he'd write out the whole word and then he'd write out an abbreviation and then it gets shorter and then the next thing you know you're back down to your most basic component.

In this example, Jake describes how his experience at the Physics First summer academy played a role in informing his beliefs about introducing ideas one component at a time; an orientation regarding the role of the teacher highlighted previously in Jake's PCK for using pie charts (see Figure 14).

Describing the source of her knowledge for using the ABC cards to assess student understandings during instruction, Findlay explains:

> One of the things I do is I give them these ABC letters that I actually got from Physics First. And so in the course of the notes I ask them questions and they have to say what they think, so I can see where they're at and

> then discuss more or less as need be based on the feedback I get from them.

This example reveals Physics First as the source of her knowledge of using ABC cards; knowledge of an assessment strategy that can be used during instruction which was highlighted previously in Findlay's PCK for using bar charts (e.g., using the ABC cards during the *Family Guy* presentation) (see Figure 23).

As another example, Allie discussed the source of her knowledge for using multiple representations to teach energy concepts, explaining:

> That's another thing I really liked about Physics First – multiple representations – show me you understand this is so many different ways, and to me that is really effective. That changed me as a teacher when I got a chance to see that.

This example highlights Physics First as an experience informing Allie's knowledge of using multiple representations to reveal student understanding; knowledge of an assessment strategy which was highlighted previously in Allie's PCK for using T-charts (e.g., students reveal understanding using T-charts and concept maps) (see Figure 12).

As a final example, discussing the source of her knowledge for using whiteboarding to assess student understanding, Allie explains:

> I never really used whiteboarding as a technique before Physics First…just hearing it all the time, you know, well justify, okay explain that, why do you think that? I knew that before, it's just that in the physics arena, just listening to people saying those things and saying well you know, justify your thinking, and it's a nice way to say it. It's another way to get kids to think.

This example highlights Physics First as the experience that informed Allie's knowledge for using whiteboarding to assess student understanding; knowledge of an assessment strategy requiring student justification highlighted previously in Allie's PCK for using pie charts (e.g., students whiteboard answers to selected problems) (see Figure 17).

These examples highlight some of the ways in which Physics First informed the development of the participants' knowledge for using the central representations to teach the topics of energy transformation and transfer. Specifically, Physics First informed the participants' curricular knowledge of the relationship between ideas within the unit (see Table 5), beliefs about introducing ideas one component at a time (see Table 4), knowledge of assessing during instruction (see Table 8), knowledge of assessing using multiple representations (see Table 8), and knowledge of assessing through student justification (see Table 8). These examples capture the participants' experiences with the Physics First project, including their training at the three summer academies as well as their interactions with the curriculum developed by the Physics First project.

Other school district-supported professional development. Beyond Physics First, which was a professional development initiative supported by the district, the participants also discussed other school district-supported professional development experiences as sources informing their knowledge for teaching. For example, Findlay explained that when she first started teaching, the "district had a really well known professional development program that eclipsed what most school districts had." She explained that part of that professional development involved working with the local power company on energy conservation. This experience informed her knowledge of some of the objects she selected for her stations and how students respond to the objects. This knowledge of curricular resources was highlighted previously in Findlay's PCK for using T-charts/vocabulary (e.g., selected lab objects that demonstrate each form of energy) (see Figure 10).

As another example, discussing her approach of beginning the unit with a common experience for the students, Findlay explains, “I started putting it more into practice when I was doing a lot of literacy strategies [through the district].” Findlay explained that her instruction in literacy strategies came from a seminar funded by the school district. In this example, Findlay describes how school district-funded professional development informed the development of her knowledge for engaging students in common experiences in the beginning of the unit; knowledge of sequencing instructional strategies highlighted previously in Findlay’s PCK for using T-charts/vocabulary (e.g., students have lab experience before introducing vocabulary and building T-chart) (see Figure 10).

As a final example, Allie discussed the experiences that informed her knowledge of using the marble activity, explaining, “When I was doing some learning styles you know manipulatives were a big thing then.” Allie explained that her instruction in learning styles came from a seminar funded by the school district. In this example, Allie describes how school district-funded professional development informed her use of manipulatives and the development of her knowledge of learning styles; knowledge of student understanding highlighted previously in Allie’s PCK for using pie charts (e.g., concrete learners need concrete representations) (see Figure 17).

These examples highlight some of the ways in which school district-supported professional development informed the participants’ knowledge for using the central representations to teach the topics of energy transformation and transfer. Specifically, school district-supported professional development informed the participants' knowledge of curricular resources (see Table 5), knowledge of sequencing instructional strategies (see Table 6), and knowledge of student learning styles (see Table 7). These examples capture the participants' experiences with school district-supported professional development (other than Physics First), including professional development both during the school year and during the summer.

Collaboration with current colleagues. During the sections of the interviews focused on the instruction related to the three central representations, the participants also identified their collaborations with their current colleagues as a source informing their knowledge for teaching. For example, describing the experiences that informed her knowledge of using the *Family Guy* interactive analogy, Findlay explains, "I have this analogy which is, actually I got this from [one of my colleagues], and then kind of tweaked it for me." In this example, Findlay explains how collaboration with current colleagues informed the development of her knowledge of using interactive instructional strategies; knowledge of specific reasons for using instructional strategies highlighted previously in Findlay's PCK for using pie charts (see Figure 15) and bar charts (see Figure 23).

At another point, Findlay discussed the source informing her decision to modify the original readings into example problems, explaining:

> This worksheet was originally a reading and it was a reading with an example...we just tried to change it into a more interactive thing I guess. I think [one of her colleagues] came up with the your turn stuff, then I changed some of the words around.

In this example, Findlay explains how collaboration with current colleagues informed the development of her knowledge for modifying curricular resources;

knowledge of curriculum highlighted previously in Findlay's PCK for using pie charts (e.g. redrew pendulum problem) (see Figure 15) and bar charts (e.g., modified readings into example problems) (see Figure 23).

Describing the experiences that informed her knowledge of using the T-chart on the SMART Board, Allie explains, "Actually, [one of my colleagues] shared that one [T-chart designed to be used on the SMART Board] with me, but we share stuff with each other. That is one she actually created and I like it a lot." In this example, Allie explains how collaboration with current colleagues informed the development of her knowledge of using a specific instructional strategy in a particular way; knowledge of using an instructional strategy highlighted previously in Allie's PCK for using T-charts/vocabulary (see Figure 11).

These examples highlight some of the ways in which the participants' collaboration with their current colleagues informed the development of their knowledge for using the central representations to teach the topics of energy transformation and transfer. Specifically, collaboration with current colleagues informed the participants' knowledge of using interactive instructional strategies (see Table 6), knowledge for modifying curricular resources (see Table 5), and knowledge of using a specific instructional strategy in a particular way (see Table 6). These examples capture the participants' recent experiences working with their current colleagues in their own school as well as in other schools. This source includes collaborations during the school year as well as during the summer and in conjunction with other professional development experiences (e.g., Physics First).

Past collaboration with experienced teachers. In addition to collaborating with their current colleagues, the participants also identified their collaborations with experienced teachers in the past as experiences informing their knowledge for teaching. For example, Jake discussed his knowledge of breaking ideas down into basic components, explaining:

> I started walking into other peoples' classes. I'd always ask first. Man, I'm telling you I think that that really helped…I started to open my eyes more to here are some other strategies to try… some of the better teachers I've ever know have done that [break ideas down]…there were two in particular [gives names]. Both really good at that, just making sure that they broke it down into its most basic components.

This example highlights how Jake's collaboration with experienced teachers early in his career played a role in shaping his knowledge of breaking ideas down into basic components; knowledge of an instructional strategy (as well as an orientation) highlighted previously in Jake's PCK for using pie charts (e.g. pie charts broken into components and reconstructed as a class) (see Figure 14) and bar charts (e.g., breaking down systems by drawing the items included in the system inside the dashed circle) (see Figure 20).

As another example, describing the experiences that informed her knowledge of using marbles to introduce pie charts, Allie explained that as a beginning teacher, she "Realized that you could use manipulatives but I never really knew why." But then she spent some time observing "older teachers who used it and believed in it and I saw what they were doing…she would make the flip shoots and all those things that the kids could use to learn with…and so I think that's probably where I got all of my ideas." This example highlights how Allie's collaboration with experienced teacher earlier in her career informed how she uses marbles to introduce pie charts; knowledge of using a specific instructional strategy for a specific reason highlighted previously in Allie's PCK for using pie charts (e.g., marble activity helps to connect the ideas of energy forms and pie charts by giving the students something tangible to work with) (see Figure 17).

These examples highlight some of the ways in which the participants' past collaboration with experienced teachers informed the development of their knowledge for using the central representations to teach the topics of energy transformation and transfer. Specifically, past collaboration with experienced teachers informed the participants' knowledge and beliefs regarding breaking ideas down into basic components (see Table 6 and Table 4) and knowledge of using specific instructional strategies for specific reasons (see Table 6). These examples capture the participants' experiences as beginning teachers during which they worked with experienced teachers in their school, including formal as well as informal collaborations.

Academic experiences as a learner of science. Beyond the experiences already discussed (e.g. Physics First, teaching experience, etc), the participants also identified their academic experiences as learners of science as experiences informing their knowledge for teaching. For example, describing the experiences that informed his reason for having students come up with definitions as a class, Jake explains, "I think also that the memorization just never really stuck with me," highlighting the influence of his learning experiences on his belief regarding having students build ideas as a class; an orientation regarding student learning highlighted previously in Jake's PCK for using T-charts/vocabulary (e.g., students develop names for energy terms based on the exploration lab) (see Figure 7) and pie charts (e.g., students build pie chart ideas through class discussion) (see Figure 14).

As another example, Findlay discussed her knowledge of breaking concepts down into basic components that build on each other, explaining, "Primarily, it's just, let's give a little piece at a time and break things down...when I first learned this, I remembered how it felt. I know what it was like…breaking things down, that's something that I do." In this example, Findlay reveals how her experiences as a learner of science played a role in shaping her knowledge and beliefs regarding breaking down concepts; knowledge of instructional strategies (as well as an orientation) highlighted in Findlay's PCK for using pie charts (e.g., walking students through the steps of building pie charts one component at a time) (see Figure 15) and bar charts (e.g., introducing bar charts by starting with pie charts and introducing bar charts one component at a time) (see Figure 23).

These examples highlight some of the ways in which the participants' experiences as learners of science informed the development of their knowledge for using the central representations to teach the topics of energy transformation and transfer. Specifically, academic experiences as a learner of science played a role in informing the participants' knowledge of instructional strategies (see Table 6) and their orientations regarding the role of the teacher (see Table 4). These examples capture the participants' experiences as students in formal academic settings where the focus of the instruction was on science content.

School district expectations. During the sections of the interviews focused on the instruction related to the three central representations, the participants also identified the school district's expectations as a source informing their knowledge for teaching. For example, Jake explains:

> [As a school district] we had to come to an agreement [on the forms of energy to include] because if we're going to test on it we had to make sure

> we used the same terminology…because we're trying to keep this really general and on essential skills, we just basically stuck with things like thermal energy, elastic energy, kinetic energy.

In this example, Jake highlights how the school district informed his knowledge of what terms to use in the energy unit; knowledge of curricular goals highlighted in Jake's PCK for using T-charts/vocabulary (see Figure 7).

Discussing her instruction for the energy unit, Findlay explained that her design of the curricular resources, such as worksheets, "Has to do with the district final because on the final they use a particular format and my kids didn't have experience with that format [in the past]." In this example, Findlay reveals how the school district informed her design of curricular resources in the energy unit; knowledge of modifying curricular resources highlighted in Findlay's PCK for using pie charts (see Figure 15) and bar charts (see Figure 23).

Discussing the goals of the energy unit in terms of the emphasis on qualitatively exploring the energy concepts (e.g., transformation, energy transfer, the Law of Conservation of Energy, work, etc), Findlay explains:

> It's not a very big unit, or it is a big unit but our district has shortened it…In theory [we planned to quantitatively revisit the unit at the end of the year] and we wanted to get into energy, work, and power. It didn't happen. So it's not reflected on the final and it's not part of any of the core review.

In this example, Findlay reveals how the district informed her knowledge regarding the length and the content in the energy unit; knowledge of the curricular goals regarding the emphasis on qualitative understandings highlighted in Findlay's PCK for using T-charts/vocabulary (e.g., identify types and forms of energy) (see Figure 10), pie charts (e.g., using pie charts to represent the Law of Conservation of Energy) (see Figure

15), and bar charts (e.g., bar charts used to represent energy transformation and energy transfer) (see Figure 23).

Discussing the difference in the depth of the goals (e.g., conceptual understanding, relationships, etc) and the corresponding curricular resources (worksheets, activities, etc) of the current energy unit as compared to the goals and resources in the old energy units, Allie explains, “Our curriculum has changed a lot over the years. We were like chemistry and physical science and we just divided it into chemistry and physics. And then we stayed in that model for quite a while and I think that changed once and then we went into Physics First, and I felt like we were pretty much expected to do what was in Physics First and all the activities that were given to us.” In this example, Allie highlights how the introduction of Physics First by the school district and the expectations placed on the teachers by the district to teach from the Physics First curriculum informed her instruction in terms of the depth of the unit goals; curricular knowledge highlighted in Allie’s PCK for using pie charts (e.g., pie charts require deeper understanding of energy transformation than simple identification) (see Figure 17), and bar charts (e.g., bar charts require deeper understanding of energy transfer than simple identification) (see Figure 27).

As a final example, discussing a source that contributed to her overall goals for the energy unit, Allie explains, “One of the things that I think about is what is the best way for me to get to my Essentials and get students to understand the meat of it?” In this statement, Allie reveals how the “Essentials” (the goals for the unit established by the school district) informed her knowledge of the goals for the energy unit; knowledge of curricular goals highlighted in Allie’s PCK for using T-charts/vocabulary (e.g., using specific terms/vocabulary that are important for future representations) (see Figure 12), pie charts (e.g., using *Family Guy* presentation to address Law of Conservation of Energy and energy transformation goals) (see Figure 17), and bar charts (e.g., car charts address the unit goal of energy transfer) (see Figure 27).

These examples highlight some of the ways in which the school district informed the development of the participants' knowledge for using the central representations to teach the topics of energy transformation and transfer. Specifically, school district expectations informed the participants' knowledge of curricular goals (content, emphasis on qualitative understandings, depth of the unit goals) and knowledge of modifying curricular resources (see Table 5). These examples capture the participants' experiences responding to the policies, guidelines, programs, etc., imposed on the participants by the school district.

Collaboration with university faculty and other university professional development. The participants also discussed how other collaborations with university faculty and other university professional development (other than Physics First) informed their knowledge for teaching. For example, explaining where he learned to have students begin the unit with some sort of engagement experience, Jake explains:

> This professor that we're working with, who through the University found out that we were teaching this physics and engineering, which there was a real strong push, so he came to us, and he threw out a bunch of different scenarios that he thought that we'd like to try and they were very effective that were the explore…So then exploring kind of started with that. And then it was kind of reiterated when we went through the Physics First program. How let's just get your fingers wet and just try to come up with some basic ideas of what we're doing and then turn that into now let's take a look at what happened and why it happened.

This example demonstrates the influence of collaborations with university faculty on the development of Jake's knowledge of beginning instruction with engagement experiences; knowledge of sequencing instructional strategies highlighted previously in Jake's PCK for using T-charts/vocabulary (e.g., began the energy unit with exploration lab) (see Figure 7).

As another example, Jake discussed the source of his knowledge for having students build understandings based on their experiences. He explained that he got the idea from reading the book *How Students Learn* when he was "doing [professional development] 10 years ago through the engineering school. We did book studies and that was neat." In this example, Jake reveals how collaboration with university faculty and university professional development informed the development of his knowledge for students building understanding based on experiences; knowledge of student understanding (as well as an orientation regarding student learning) highlighted previously in Jake's PCK for using T-charts/vocabulary (e.g., students develop names for energy terms based on the exploration lab) (see Figure 7).

These examples highlight some of the ways in which collaborations with university faculty informed the participants' knowledge for using the central representations to teach the topics of energy transformation and transfer. Specifically, collaborations with university faculty and other university professional development informed the participants' knowledge of sequencing instructional strategies to begin with engagement experiences (see Table 6), and their knowledge of student understanding and orientation regarding students building understanding based on experiences (see Table 4). These examples capture the participants' experiences collaborating with university faculty and participating in university-sponsored professional development (excluding Physics First and school district-supported professional development).

Non-academic life experiences. Finally, the participants discussed how their non-academic life experiences informed their knowledge for teaching. For example, Jake explained how his experiences coaching basketball informed his knowledge of introducing representations early in the unit that explain the current concept as well as future concepts. He explains that when coaching, he would:

> Have the kids do what is called a crossover layup and they're like why in the heck would I ever do a crossover layup…but by the end, the kids know why they have to do that specific type of layup…and I think that is true in the classroom too. Getting them, leading them in the right direction, making sure that they understand they know why they are doing the things that they do. And not necessarily know, but doing them so that something in the future will come back and say now I know why I did this. I'll give you a perfect example. So, today you videotaped a class where I drew a dashed circle around the system. And I know the kids are thinking why do I have to bother circling the system. Why is it a dashed circle? So then, from there we go to the bar graphs, there's a dashed circle in the middle of the bar graphs. And then they associate the fact that that means the system.

This example demonstrates how Jake's experiences as a basketball coach informed how he introducing representations early in the unit that explain the current concept (e.g., system circle used to distinguish the system from the environment during beginning of the unit) as well as future concepts (e.g., system circle used in bar charts to facilitate understanding of energy transfer); knowledge of sequencing instructional strategies (see Table 6) highlighted previously in Jake's PCK for using T-charts/vocabulary (see Figure 7) and bar charts (see Figure 20).

Summary. As is evident in the descriptions, not all of the experiences or sources described above were shared by all three participants. However, viewed collectively through the lens of phenomenography, these descriptions highlight the different categories of experiences and sources that contributed specifically to the participants' development and change of knowledge for using the three central representations in their instruction on energy. The nine categories, or outcome space, capture the variation in the participants' conceptions of the experiences that informed this knowledge development. The outcome space included: 1) teaching experience, 2) Physics First, 3) other school district-supported professional development 4) collaboration with current colleagues, 5) past collaboration with experienced teachers, 6) academic experiences as a learner of science, 7) school district expectations, 8) collaboration with university faculty and other university professional development, and 9) non-academic life experiences

Experiences Corresponding to Representations in the Entire Energy Unit

The purpose of the second phase of the analysis of the experiences and sources informing the development of the participants' knowledge for using representations to teach energy was to look for additional support for the categories of experiences and sources included in the outcome space as well to provide an indication of the relative significance or prominence of specific experiences on the development of the participants' knowledge. Whereas the first phase of the analysis only focused on the sections of the transcript where the participants discussed their instruction regarding the central representations, this phase of the analysis focused on the entire set of transcripts, during which the participants were asked about every representation that they used for the entire energy unit. This included the sections of the transcript discussed above (i.e., the three central representations) as well as every additional discussion about the representations used throughout the course of the interviews. The results of this analysis are summarized in Table 9.

Table 9

Sources Informing the Participants' Use of Representations and Strategies as Identified Throughout the Entire Energy Unit

Source	Representation or Strategy Informed
Teaching experience	Marble activity, video clips, vocabulary, symbols, concept sequence, breaking down concepts, stations, level of direct instruction, system circle, exploring ideas, sketches, student difficulties, student misconceptions, SMART Board, T-chart, analogies, examples, demonstrations, novel ideas, multi-step problems, non-energy symbols, easy to complex problems, pie charts tied to Law of Conservation of Energy, modifying curriculum
Physics First	Scenarios, breaking down concepts, multiple representations, stations, graphic energy representations, simulations, subject matter, goals, ABC cards, whiteboarding, identifying systems, identifying states, handouts, pie charts tied to Law of Conservation of Energy, bar charts, introducing ideas a component at a time, equations for Law of Conservation of Energy, symbols, non-energy symbols, work arrow
Other school district-supported professional development	Scenarios, symbols, goals, concept sequence, explain after explore, video clips, vocabulary, real life examples, stations objects, begin with common experience, marble activity, formative assessment
Collaboration with current colleagues	Family Guy analogy, video clips, T-chart, scenarios, test questions and format, system circle, analogies, breaking down concepts, pie charts, bar charts, modifying worksheets
Past collaboration with experienced teachers	Marble activity, breaking down concepts, analogies, novel ideas, concept maps
Academic experiences as learner of science	Student difficulties, sketches, pie charts, bar charts, how people learn, breaking down concepts
School district expectations	Goals, participating in Physics First, assessments, terminology
Collaboration with university faculty and other university professional development	Stations, building on ideas
Non-academic life	Introducing the system circle, learning by association, examples

experiences	

The results of the analysis revealed that a total of nine categories of sources and experiences contributed to the participants' knowledge and use of representations for the entire energy unit, specifically, 1) teaching experience, 2) Physics First, 3) other school district-supported professional development 4) collaboration with current colleagues, 5) past collaboration with experienced teachers, 6) academic experiences as a learner of science, 7) school district expectations, 8) collaboration with university faculty and other university professional development, and 9) non-academic life experiences. The table highlights how some of the sources (e.g., teaching experience) informed a large number of representations, strategies, or knowledge components throughout the entire energy unit, while other sources (e.g., non-academic life experiences) informed fewer representations, strategies, or knowledge components throughout the entire energy unit.

The results of the analysis of the experiences and sources informing the participants' knowledge of using representations as highlighted in Table 9 inform the categories of experiences and sources included in the outcome space in two ways. First, the analysis revealed that the categories of experiences and sources informing the participants' knowledge of using representations throughout the entire unit were the same as the categories informing the representations not directly connected to the three central representations. That is, the analysis did not reveal any additional categories, nor did the analysis contradict the categories in the initial outcome space. These findings support the inclusion of the nine categories identified in the outcome space and do not suggest that additional items need to be added to the outcome space.

Second, the results highlighted in Table 9 reveal that some of the experiences and sources played a more prominent role in the development of the participants' knowledge as compared to the other experiences and sources. Specifically, teaching experience, Physics First, other school district-supported professional development, and collaboration with current colleagues informed a larger number of representations, strategies, and knowledge components when compared to the other five items identified in the outcome space.

In the following section, I will describe and highlight the characteristics and features of the categories of experiences and sources included in the outcome space. These descriptions will help to inform the discussion regarding how specific experiences and sources informed the representations and knowledge components, as well as the discussion as to why certain experiences and sources were more prominent than others.

Descriptions of the Experiences and Sources Corresponding to the Participants' Instruction for the Entire Unit

In the following section, I will describe the categories of experiences and sources identified in the outcome space by: 1) providing a brief description of the experience or source, 2) highlighting the characteristics of the experience or source through excerpts from the interview transcripts, and 3) summarizing the characteristics of the experience or source. I will follow this pattern for all nine categories of experiences and sources identified in the outcome space. As a reminder to the reader, in order to avoid unnecessary repetition, and because the emphasis of this phase of the analysis was on capturing the characteristics of the experiences (versus the connections between the experiences and specific components of PCK), I did not re-emphasize the connections between the experiences and the specific knowledge components informed by the experiences. Instead, I only focused on the connections between the specific experiences identified in the outcome space and any characterization of those experiences. However, in some cases, the sections of the interviews informing this phase of the analysis regarding the characteristics of the participants' experiences are the same as the sections of the interviews that informed the previous analysis regarding the identification of the representations and the connections between the experiences and the specific knowledge components. However, because this analysis focused on all of the representations used throughout the unit (instead of just the three central representations), and focused on the descriptions of the characteristics of the experiences, I drew from a larger number of descriptions in the interviews when compared to the previous analysis.

Teaching Experience. The source "Teaching Experience" captures the participants' experiences teaching junior high science throughout their careers, including their interactions with students, their use of instructional strategies, their interactions with the curriculum, and their utilization of assessments while teaching multiple subjects and topics. However, the focus is only on their experiences teaching in their classrooms, not on other experiences associated with teaching, such as collaboration with other teachers or professional development activities.

Jake. Discussing teaching experiences that have informed his knowledge of breaking concepts into basic components, Jake explained:

> The more I see kids and I see where they are confused, the more I start to realize that boy, if I could have a do-over how I would have done it differently. I think that just paying attention to detail. It's like a test question. If you write a test question that is ambiguous enough where it hits two concepts in the question, I'm not going to say it's a bad question by any means. But you will never know why they missed the question

> because it covers two different, two pieces of content. If it only covers one, you know exactly why it doesn't. And so I think in teaching it's the same way. If students miss problems, you have to figure out why they missed them. And if you break it down into its most basic components, it becomes really easy to figure that out.

In this explanation, Jake reveals that one of the characteristics of his teaching experience that informed his knowledge of using representations was recognizing student confusion during instruction and on assessments. At another point, Jake discussed his knowledge of the need to establish ground level as a class. He explains, "It's common [students not knowing where ground level is], it happens every year in every class. They don't know exactly where so they make a guess." Similar to the previous example, in this explanation, Jake reveals that a characteristic of his teaching experience that informed his knowledge of using representations was knowing common areas of student confusion based on teaching the topic in multiple years.

At another point, Jake discussed how his teaching experience informed his knowledge of specific student misconceptions. He explained:

> The older you are, the more that you teach, the more you already know what kinds of questions the kids are going to ask…eventually you get to the point where you've said the same thing so many times that you don't have to think about it.

In this explanation, Jake reveals that another characteristic of his teaching experience that informed his knowledge of using representations was knowing what kinds of questions students will ask based on teaching the topic for multiple years. Jake also discussed how his teaching experience informed his knowledge of introducing the dashed system circle early in the unit. Jake explained that his knowledge was informed by:

> Trial and error – the first time I did it [taught the Physics First energy unit], man, you take a look at the test that I gave, they were bombing similar [types of] questions. Not doing terrible, but there were definitely patterns in the problems that they were missing. And then the next year that I gave it, you start to break it down a little bit more and make adjustments and it becomes easier. And of course the third or fourth year that you finally get through to it, you started to figure out, oh, if I do this right now, it makes it really easy for the kids to understand.

In this explanation, Jake reveals that another characteristic of his teaching experience that informed his knowledge of using representations was trial and error, specifically, trying out approaches to breaking down instruction on representations and evaluating the success of the approaches by examining student assessments. During the interviews, Jake also discussed how his teaching experience informed his knowledge of organizing the exploration lab. Jake explains, “To be honest, I think that mostly just trial and error. The fact that I’ve been out there and I’ve tried this and tried this.” Again, this example highlights trial and error as a characteristic of Jake’s teaching experience that informed his instruction using representations.

Discussing how his teaching experience informed his knowledge of when to use the pendulum demo in the sequence of instruction, Jake explains:

> I think just thinking about it. The fact that I knew that I had it and when I looked at the content of what I had to cover, it just popped into my head. I thought this would be a great time to introduce this.

In this example, Jake reveals how considering an existing instructional strategy in light of new content served as a characteristic of his teaching experience that informed his knowledge of using representations. Jake also discussed how his teaching experience informed his knowledge of sketching and manipulating objects on the SMART Board. He explains, “That’s strictly playing around, because they give you a little basic training on it but it’s like you at the computer program. The more you play around with it the better you get at it. And with the SMART Board it's the same way." This example highlights the act of spending time exploring and using technology as a characteristic of Jake's teaching experience that informed his instruction using representations.

As a final example, discussing the problems that he selected from Physics First curriculum to address establish a reference point for ground level, Jake explains that knowing which problems to select:

> Is something that you don't recognize [your first time teaching it]. But after you teach it the first time, then it comes back as oh, that would have been good here or you should have left this off at this point and moved it back, or you should have moved this one up.

In this explanation, Jake reveals that another characteristic of his teaching experience that informed his knowledge of using representations was recognizing the better problems and placement of those problems within the curriculum after teaching the topic at least once.

In these statements, Jake reveals the characteristics of his teaching experience that have informed his knowledge for using representations, including recognizing student confusion during instruction and on assessments, knowing common areas of student confusion based on teaching the topic in multiple years, knowing what kinds of questions students will ask based on teaching the topic for multiple years, breaking down instruction on representations and evaluating the success of the approaches by examining student assessments, considering an existing instructional strategy in light of new content, spending time exploring and using technology, and recognizing the better problems and examples within the curriculum after teaching the topic at least once. These characteristics are also captured in Table 10 at the end of this section (along with the other participants' descriptions).

Findlay. Discussing the teaching experiences that have informed her instruction, Findlay explained that her knowledge of introducing the pendulum demonstration prior to introducing pie charts was informed by her "experiences with kids when you are like oh my gosh, they are clueless, and so you start working backwards… [based in part on] whatever they've turned in." In this explanation, Findlay reveals that another characteristic of her teaching experience that informed her knowledge of using representations was recognizing student confusion during instruction and on assessments. As another example of this characteristic of her teaching experience, Findlay discussed her knowledge of introducing energy vocabulary words prior to energy symbols, explaining:

> If I gave [the students] the abbreviations from the get-go, [they're] not writing the words "kinetic", [they're] not writing the words "potential," [they're] not writing "gravitational" and that sort of thing. Then, we move on and I have a class of kids that are throwing out letters and they'll be like 'PM' [but] there's no potential mechanical. So what happened with them, they weren't [understanding], do you know what I mean, because it all came at once.

In this example, Findlay again reveals that recognizing student confusion during instruction and on assessments (i.e., student responses during class) was a characteristic of her teaching experience that informed her knowledge of using representations.

At another point, Findlay explained that her knowledge of breaking concepts into basic components was shaped through:

> My experience of how kids screw up and misunderstand and misinterpret…I think a lot of it is just trial and error. I mean, I've had enough years of trial and error. You get it five times a day, every day for sixteen years now.

In this explanation, Findlay reveals that one of the characteristics of her teaching experience that informed her knowledge of using representations was trial and error.

Specifically, knowing common areas of student misunderstanding or confusion based on teaching the topic in multiple years. As another example of this characteristic of her teaching experience, discussing her knowledge of connecting pie charts to the Law of Conservation of Energy, Findlay explains:

> The first year we did the energy unit I found that kids were not making that connection. So, I probably hit the Law of Conservation of Energy a little bit differently as I taught this year after year because I started seeing, okay, so they are just writing letters in circles and not making the connection about the percentages.

In this example, Findlay again reveals the characteristic of recognizing common areas of student confusion based on teaching the topic in multiple years. At another point, Findlay also discussed her knowledge of providing a structured data collection chart for the students to use during the exploration lab. She explains:

> One reason is because I got feedback, like for instance, in this class [two students] gave me feedback. They were like, they want to know how many lines to skip. I mean, they wanted that much structure, and so I'm just trying to give them examples of how to organize stuff so that it's useful.

In this explanation, Findlay reveals that another characteristic of her teaching experience that informed her knowledge of using representations was listening to student feedback regarding how much structure they want.

Discussing her knowledge of breaking instruction down into smaller components (e.g., students take notes, students come up with examples, discuss as class), Findlay explains:

> What I found is that, if I kind of broke it down a little bit that they kept more of it. As opposed to 'this is the kind of energy, if it's a kinetic energy and this is the abbreviation. Okay, next one.' They didn't keep it.

In this example, Findlay reveals that another characteristic of her teaching experience that informed her knowledge of using representations was breaking down instruction on representations and evaluating the success of the approaches based on student understanding.

During an interview, Findlay also discussed her knowledge of demonstrating the first exploration lab station. She explains that historically, she was:

> Not getting what I want. So it's like, well that didn't work out, let's see what we can do the second hour. And actually with a lot of those explore labs…I felt that I ended up having a lot of toys flying through the room. A lot of laughing and carrying on and a lot of empty lab books.

In this explanation, Findlay reveals that another characteristic of her teaching experience that informed her knowledge of using representations was recognizing that students were not achieving the objectives of the instructional strategy in previous years' instruction.

At another point, discussing her decision to modify the original reading about bar charts into example problems, Findlay explains:

> After you teach it the first year, then you figure out okay, this is what they have trouble with. Or, if sometimes this example sucks, forget it and bring in something else. This was originally a reading and it was a reading with an example…and so we just tried to change it into a more interactive thing.

In this explanation, Findlay reveals that another characteristic of her teaching experience that informed her knowledge of using representations was recognizing better examples and problems within the curriculum after teaching the topic at least once. At another point, discussing her knowledge of changing the system circle to a system box, Findlay explains:

> In the Physics First material, it is a circle in between the two bar charts from the initial and final state, and what I found was kids were getting confused between pie charts and that circle. So when it first came up, I was like where is this coming from, and then as I got more into it I was like they think it is a pie chart that is embedded in the bar chart. So no

> wonder I was getting all this junk. Then I realized I have this wonderful analogy of Stewy's bedroom [in the *Family Guy* analogy] and we always tell them to draw a box around your system and that goes through even when you get into forces and everything, so why not just make it a box.

In this example, Findlay reveals that another characteristic of her teaching experience that informed her knowledge of using representations was making changes in the curricular materials based on identifying student confusion via student work.

In these statements, Findlay reveals characteristics of her teaching experience that have informed her knowledge for using representations, specifically, recognizing student confusion during instruction and on assessments, knowing common areas of student misunderstanding or confusion based on teaching the topic in multiple years, listening to student feedback regarding how much structure they want, breaking down instruction on representations and evaluating the success of the approaches based on student understanding, recognizing that students were not achieving the objectives of the instructional strategy in previous years' instruction, recognizing better examples and problems within the curriculum after teaching the topic at least once, and making changes in the curricular materials based on identifying student confusion via student work. These characteristics are also captured in Table 10 at the end of this section (along with the other participants' descriptions).

Allie. Discussing some of the teaching experiences that informed her knowledge of introducing terminology in gradual steps, Allie explains that she "learned from experience. It's going back to that whole thing to where you feel like you've been very obvious, and you find out later that they completely missed what you wanted them to get." In this example, Allie reveals that another characteristic of her teaching experience that informed her knowledge of using representations was recognizing student confusion during instruction. As another example of this characteristic of her teaching experience, Allie explained that changes in her instruction (e.g., focusing on vocabulary and fewer representations) were informed "when I backed up and said, they are not getting it, they are not able to take what I taught them and put it in a brand new situation." Again, this example reveals that recognizing student confusion during instruction and on assessments (i.e., applying ideas in new situations) is a characteristic of Allie's teaching experience.

Allie also discussed her knowledge of providing the students with experiences before vocabulary. She explains:

> I just think it came down to finally getting the fact that you left kids behind sometimes and you didn't even realize it. You kind of just took off and you had no clue that where they were you thought they got it but when you went back and really dug deeper and said what does that mean? They couldn't tell you and then you started to back up and say, hang on a second, I'm not achieving what I want to achieve

In this example, Allie provides another example that highlights the teaching experience characteristic of recognizing student confusion during instruction and on assessments. During an interview, Allie also discussed her knowledge of introducing the types of energy and the forms of energy at different times in the unit. She explains:

> If you give it to them all at once, then sometimes they get confused about it. At least that has been my experience about it they get a little bit confused about it because they are thinking, are those two types of energy and I have all these different forms, and they get forms and types mixed up…I think working with them and seeing that they got confused about it

In this example, Allie reveals that another characteristic of her teaching experience that informed her knowledge of using representations was knowing common areas of student misunderstanding or confusion based on teaching the topic in multiple years.

Allie also discussed her knowledge for engaging students in experiences early in the unit. She explains:

> For me I guess it's just seeing the result of not engaging, which is you fight with them and there are days when you don't engage them although you wanted to. And it just feels like more of a fight. There's more resistance to learning, there's more you just don't feel like they're engaging with you.

In this example, Allie reveals that another characteristic of her teaching experience that informed her knowledge of using representations was experiencing student resistance to learning when not engaged. As a final example, Allie discussed her knowledge of having students share their ideas with the rest of the class (e.g., whiteboarding). She explains:

> It comes from experience because you realize that kids are not really tolerant of the same stuff over and over again. It's boring for them, and you've got to find ways to change it up and keep them interested, and keep them engaged

In this example, Allie reveals that another characteristic of her teaching experience that informed her knowledge of using representations was recognizing students' intolerance for repetition of assessment strategies.

In these statements, Allie reveals characteristics of her teaching experience that have informed her knowledge for using representations, specifically, recognizing student confusion during instruction and on assessments, knowing common areas of student misunderstanding or confusion based on teaching the topic in multiple years, experiencing student resistance to learning when not engaged, and recognizing students' intolerance for repetition of strategies.

Taken together, the participants' statements and explanations paint a picture of the types of teaching experiences that informed the participants' knowledge for teaching.

The characteristics for all of the participants are highlighted in the Table 10. Additionally, characteristics that are shared between the participants are identified.

Table 10

Characteristics of the Participants' Teaching Experience that Have Contributed to Their Knowledge for Using Representations

Characteristics of Teaching Experience
• [3]Recognizing student confusion during instruction and on assessments
• [3]Knowing common areas of student confusion based on teaching the topic in multiple years
• Knowing what kinds of questions students will ask based on teaching the topic for multiple years
• Listening to student feedback regarding how much structure they want
• Experiencing student resistance to learning when not engaged
• Recognizing students' intolerance for repetition of strategies
• [2]Breaking down instruction on representations and evaluating the success of the approaches by examining student assessments
• Considering an existing instructional strategy in light of new content
• Recognizing that students were not achieving the objectives of the instructional strategy in previous years' instruction
• [2]Recognizing the better problems and examples within the curriculum after teaching the topic at least once
• Spending time exploring and using technology
• Making changes in the curricular materials based on identifying student confusion via student work

Note: Characteristics that are shared between two participants are indicated with a ([2]) and characteristics shared between all three participants are identified with a ([3]).

Physics First. The source "Physics First" captures the participants' experiences with the Physics First project, including their training at the three summer academies as well as their interactions with the curriculum developed by the Physics First project. However, it does not include experiences that were associated with the Physics First project such as collaborating with other teachers unless those activities were explicitly connected to Physics First.

Jake. Discussing how Physics First informed his knowledge of beginning with an exploration lab from which students build understanding, Jake explained:

> [It was] reiterated when we went through the Physics First program. How let's just get your fingers wet and just try to come up with some basic ideas of what we're doing and then turn that into now let's take a look at

> what happened and why it happened. And then get into it with more detail, a more detailed look at what happened and why it happened

In this explanation, Jake reveals that one of the characteristics of Physics First that informed his knowledge of using representations was his participation in exploring an idea (i.e., getting his fingers wet) and then investigating what happened and why it happened. Jake also discussed how Physics First informed his knowledge of beginning with an exploration experience and building understanding. He explains:

> Everything you did was, okay, let's take a look at this. Now, can you design an experiment on it? And then once you do, the results that you got from your experiment, those are, explain to me what did those results mean…And now that you have a deep understanding of what it means, can you apply that to what happens if you do this. And what happens if you do this? What happens if you see this…and I think that's, to me, that's what really gets me into thinking.

In this explanation, Jake again reveals that one of the characteristics of Physics First that informed his knowledge of using representations was participation in exploring an idea and then investigating what happened and why it happened. At another point, Jake also discussed how Physics First informed his knowledge of building representations one component at a time. He explains, "It's not just that Physics First makes you do it. I think it's once you see it happening and how it works, then you start to do it on your own for everything that you teach." In this explanation, Jake reveals that two of the characteristics of Physics First that informed his knowledge of using representations were: 1) participating in building representations and 2) observing strategies and how they work.

Jake also discussed how Physics First informed his knowledge of introducing representations in basic components that build on each other. He explains:

> I learned a lot from [one of the Physics First instructors]. A perfect example for [the instructor] is doing representations, and how you take one thing but then it leads to another thing, which leads to another thing, and he makes it seem so simple at how it leads. Here's a perfect example. Just like we talked about these representations for the symbols for the types of energy, [the instructor is] doing motion diagrams and he's drawing car after car after car after car on the whiteboard. And he does this for an hour. And then all of a sudden he says is it okay if I just draw a dot for a car? And the next thing you know it's dots. But it was so simple to say okay, here's a dot. He converted from cars to dots in 10 seconds but it made total sense and then from here on, and people didn't realize this, but all of the activities were just dots. And he had made that simple conversion to dots in 2 seconds and he had an explanation as to why it was a dot and the explanation was that it was simple. He did that a whole lot. Okay, so that leads to this and this leads to this.

In this explanation, Jake reveals that one of the characteristics of Physics First that informed his knowledge of using representations was observing the instructors as they demonstrated or modeled instructional strategies. At another point, Jake discussed how Physics First informed his knowledge of using problems and questions. He explains:

> Whenever they would assign problems, a lot of the problems were actually classified into different groups. Like you should whiteboard questions number 1, 2 and 3. You should assign number 6,7, and 8 for homework, and 9 and 12 should be an enrichment project or an advanced question…I liked the fact that it just challenged kids in a different way. You could always with the physics assignments, you could always have expectation level at level A, or step it up to level B or C, and then you could take that to the abilities of your classes.

In this explanation, Jake reveals that one of the characteristics of Physics First that informed his knowledge of using representations was being provided with problems and questions of varying difficulty to be used for different purposes. Finally, Jake discussed the curriculum provided by Physics First. He explained, "I love all the new lab activities, all the different ideas, I like how it's set up." He discussed that this included being provided curricular resources (e.g. lab activities, worksheets), ideas for representing energy concepts (e.g., pie charts, bar charts, etc), and possible learning objectives.

In these statements, Jake reveals the characteristics of his teaching experience that have informed his knowledge for using representations, including participation in exploring an idea and then investigating what happened and why it happened, participating in building representations, observing strategies and how they work, observing the instructors as they demonstrated or modeled instructional strategies, being provided with problems and questions of varying difficulty to be used for different purposes, being provided curricular resources, being provided ideas for representing energy concepts, and being provided possible learning objectives. These characteristics are also captured in Table 11 at the end of this section (along with the other participants' descriptions).

Findlay. Discussing how the Physics First academy informed her knowledge for using representations, Findlay explains:

> I think I just learned more tricks to put in my bag, and they're good things. Because one of the things, just talking and reflecting and thinking about it, the kids we teach are changing. They're so not the way they were before.

In this explanation, Findlay reveals that one of the characteristics of Physics First that informed her knowledge of using representations was learning about instructional strategies (i.e. tricks) for teaching students. She explained that these strategies included ideas for representing energy concepts in multiple ways (e.g. pie charts, bar charts), strategies for assessment (e.g., ABC cards), and participating in strategies for justifying ideas (e.g. sharing out ideas via whiteboarding). She explains, "When I first started teaching, there wasn't a lot of stand up in front of the class and share your views and give your opinion and that sort of thing. And that definitely, there is more of that."

Findlay also explained that, “I needed some fresh ideas and some different things to do so that I could find ways to apply them.” She discussed that this included being provided with new curricular resources (e.g., lab activities, worksheets) and receiving new technology (e.g., computers, lab equipment). She explains, “You know students are so much more technologically savvy and those sorts of things, and Physics First brought a lot of those opportunities for me.”

In these statements, Findlay reveals characteristics of her experiences with Physics First that informed her knowledge for using representations, specifically, being provided ideas for representing energy concepts in multiple ways, being provided strategies for assessment, participating in strategies for justifying ideas, being provided new curricular resources, and receiving new technology. These characteristics are also captured in Table 11 at the end of this section (along with the other participants' descriptions).

Allie. Discussing how the Physics First informed her knowledge of using multiple representations, Allie explains:

> That's something I really liked about physics first – multiple representations. Show me you understand this is so many different ways, and to me that is really effective. That changed me as a teacher when I got a chance to see that. I said, wow, that is really neat that we're asking them to do the same thing so many different ways.

In this example, Allie reveals that one of the characteristics of Physics First that informed her knowledge of using representations was observing strategies and how they work, specifically, observing multiple representations being used for instruction and assessment. Additionally, this example reveals that Allie was provided ideas for representing energy concepts (i.e., multiple representations). At another point, Allie discussed her knowledge of having students justify their ideas. She explains:

> Getting kids to think and share with each other and justify why they're thinking, that was something I picked up from Physics First that I liked…just hearing it all the time, you know, well justify, okay explain that, why do you think that?

In this example, Allie again reveals that one of the characteristics of Physics First that informed her knowledge of using representations was observing strategies and how they work, specifically, observing other teachers being asked to justify and explain their ideas. At another point, discussing her knowledge of using whiteboards as an assessment strategy, Allie explains, "Well basically yeah, [she learned how to whiteboard by] just having to do it all of the time." In this example, Allie reveals that two of the characteristics of Physics First that informed her knowledge of using representations were participating in, and being provided, strategies for justifying ideas, specifically, whiteboarding as a student in the class.

Finally, Allie explained that her physics content knowledge "really developed in those three years [of the Physics First project] because I had a lot of exposure [to the content], which was good." In these statements, Allie reveals that one of the characteristics of Physics First that informed her knowledge of using representations was receiving instruction in the energy content. Allie also discussed that her knowledge of the content was facilitated by receiving and working through the curricular resources (e.g. worksheets, lab activities).

In these statements, Allie reveals characteristics of her experiences with Physics First that informed her knowledge for using representations, specifically, observing strategies and how they work, being provided ideas for representing energy concepts, participating in strategies for justifying ideas, being provided strategies for justifying ideas, receiving instruction in the energy content, and receiving and working through the curricular resources.

Taken together, the participants' statements and explanations paint a picture of the types of teaching experiences that informed the participants' knowledge for using representations. The characteristics for all of the participants are highlighted in the Table 11. Additionally, characteristics that are shared between the participants are identified.

Table 11

Characteristics of Physics First that Have Contributed to the Participants' Knowledge for Using Representations

Characteristics of Physics First
• [2]Observing strategies and how they work
• [2]Participating in strategies for justifying ideas
• Participation in exploring an idea and then investigating what happened and why it happened
• Participating in building representations
• Observing the instructors as they demonstrated or modeled instructional strategies
• [3]Being provided curricular resources
• [3]Being provided ideas for representing energy concepts
• Being provided possible learning objectives
• Receiving new technology
• Working through the curricular resources
• Being provided with problems and questions of varying difficulty to be used for different purposes
• [2]Being provided strategies for assessment
• Observing instructors model assessment strategies

Note: Characteristics that are shared between two participants are indicated with a ([2]) and characteristics shared between all three participants are identified with a ([3]).

Other school district-supported professional development. The source "Other School District-Supported Professional Development" captures any of the participants' experiences with school district-supported professional development other than the Physics First project. These experiences include professional development both during the school year and during the summer.

Findlay. Discussing other school district-supported professional development that informed her knowledge of using real-life energy examples (e.g., nuclear energy), Findlay explains:

> A lot of the professional development took us places to see stuff…one time we went to the dump, and we went to the water treatment plant, we went to the power plant. So I was going all over, looking at resources that were connected to the science field or practical applications to the science field… it was really cool to be able to explain those things to kids because that's like everyday science.

In this example, Findlay reveals that one of the characteristics of other school district-supported professional development that informed her knowledge of using representations was visiting different facilities and making practical connections to science. Discussing another school district-supported professional development program that informed her knowledge of real-life examples and objects for the exploration lab, Findlay explained that during the school year, employees of the local utility company would:

> Come into our classroom, instead of going to the office that day, they come to our classroom. They would introduce a program and they would have books for all the kids and they did some activities that have to do with like energy conservation and things like that…and because they were an email or phone call away all the time, I would call them and I'd say like how many gigawatts are we ordering today?

In this example, Findlay reveals that two of the characteristics of other school district-supported professional development that informed her knowledge of using representations were: 1) professionals providing programs, activities, and resources connected to energy and 2) having easy access to professionals for questions.

As a final example, Findlay discussed her knowledge for beginning the unit with a common experience. She explains:

> I put it more into practice when I was doing a lot of literacy strategies…I had signed up for a yearlong, kind of a professional learning thing where [another teacher] and I, we were pulled out of class once every six weeks to meet with [a district coordinator]…And what we did was, we met, like I said, every six weeks. They had a sub for us. Either half a day or a full day sub, and we would go and do learning strategy stuff for kids with learning disabilities.

In this example, Findlay reveals that one of the characteristics of other school district-supported professional development that informed her knowledge of using representations was being provided a break from teaching to work on literacy training with a colleague.

In these statements, Findlay reveals characteristics of her experiences with school district-supported professional development that informed her knowledge for using representations, specifically, visiting different facilities and making practical connections to science, professionals providing programs, activities, and resources connected to energy, having easy access to professionals for questions, and being provided a break from teaching to work on literacy training with a colleague. These characteristics are also captured in Table 12 at the end of this section (along with the other participants' descriptions).

Allie. Discussing some of the school district-supported professional development that has informed her knowledge of different student learning styles, Allie explains, "We had somebody come in that trained us here [in different learning styles (e.g., kinesthetic, auditory, etc)] and then I went somewhere else into a classroom, in a school." In this example, Allie reveals that one of the characteristics of other school district-supported professional development that informed her knowledge of using representations was being provided training connected to how students learn in different ways. At another point, Allie discussed that her knowledge of how students learn was also informed by a school district-supported professional development program focused on student behaviors. She explains that during the program, she:

> Visited some schools in [another city]…we went to see a model school…we listened to [an expert] speak, and just loaded up the team and went up there and we brought [the ideas] back to the schools and we piloted it…[some of the ideas were] just talking about the differences in kids, form different socio-economic statuses even, really makes a difference.

In this example, Allie reveals that two of the characteristics of other school district-supported professional development that informed her knowledge of using representations were: 1) observing model schools that focus on accounting for differences in students and 2) listening to an expert speak about the differences between students.

Finally, Allie discussed that her knowledge of the goals and objectives for the energy unit were informed by a school district-supported professional development program in which she and a group of other teachers:

> Looked at the vision of our school, we looked at our goals of our school, you know changing the things that happen inside the school with achievement…and we spent a lot of time and energy on that, probably two or three years.

In this example, Allie reveals that one of the characteristics of other school district-supported professional development that informed her knowledge of using representations was working with a team to examine the goals of the school in light of the energy unit.

In these statements, Allie reveals characteristics of her experiences with school district-supported professional development that have informed her knowledge for using representations, specifically, being provided training connected to how students learn in different ways, observing model schools, listening to an expert speak about the differences between students, and working with a team to examine the goals of the school in light of the energy unit.

Taken together, the participants' statements and explanations paint a picture of the types of experiences with school district-supported professional development that informed the participants' knowledge for using representations. These experiences are highlighted in the Table 12.

Table 12

Characteristics of the Participants' Experiences with School District-Supported Professional Development that Have Contributed to Their Knowledge for Using Representations

Characteristics of Other School District-Supported Professional Development
• Visiting different facilities and making practical connections to science • Professionals providing programs, activities, and resources connected to energy • Having easy access to professionals for questions • Being provided a break from teaching to work on literacy training with a colleague • Being provided training connected to how students learn in different ways • Observing model schools that focus on accounting for differences in students • Listening to an expert speak about the differences between students • Working with a team to examine the goals of the school in light of the energy unit

Collaboration with current colleagues. The source "Collaboration with Current Colleagues" captures the participants' recent experiences working with their current colleagues in their own school as well as in other schools. This source includes collaborations during the school year as well as during the summer and in conjunction with other professional development experiences (e.g., Physics First).

Jake. Discussing the collaborations with current colleagues that informed his knowledge for using simple assessments during instruction (e.g., holding fingers up), Jake explains:

> I have been observing a lot of classes over the last couple of years and one of the things that I've realized is no matter how well you think you've taught it, it doesn't mean that the students are getting it…So what I'm trying to be is much more efficient teacher, making sure that before I move on they've got it…but the key with the [assessment strategies] for me is it's got to be time efficient. You can't take a lot of time. It's got to be a real short, sweet, and to the point

In this example, Jake reveals that one of the characteristics of his collaboration with current colleagues that informed his knowledge of using representations was observing his colleagues' classes and paying attention to student understanding. At another point, Jake discussed his knowledge of using analogies. He explains, "A lot of the analogies come from other teachers. Just have you thought about this, when we get together somebody will say this is what I did, even district wide." In this example, Jake reveals that another characteristic of his collaboration with current colleagues that informed his knowledge of using representations was informally discussing strategies (i.e. analogies) with other teachers. These characteristics of Jake's collaboration with current colleagues that informed his knowledge for using representations, specifically, observing his colleagues' classes and paying attention to student understanding and informally discussing strategies with other teachers are captured in Table 13 at the end of this section (along with the other participants' descriptions).

Findlay. Discussing her collaborations with current colleagues that informed her knowledge of student difficulties, Findlay explains, "We have those conversations, always, like where are you at, what are you doing, how is that going." In this example, Findlay reveals that one of the characteristics of her collaboration with current colleagues that informed her knowledge of using representations was informally discussing strategies with other teachers (e.g., what they are doing and how it is going). Findlay also discussed that one of her colleagues "teaches in my room first hour, so I can see what she's doing and I can, half of the time I'm in the room while she's teaching, so I can see the roadblocks." In this example, Findlay reveals that one of the characteristics of her collaboration with current colleagues that informed her knowledge of using representations was observing her colleague's classes and paying attention to student understanding.

As a final example, Findlay explains, "The first year I taught this energy unit…I was emailing [two of her colleagues] all the time going what are you guys doing? This is not working for me." In this example, Findlay reveals that two of the characteristics of her collaboration with current colleagues that informed her knowledge of using representations were: 1) asking for instructional advice from colleagues and 2) sharing resources with colleagues.

In these statements, Findlay reveals characteristics of her collaborations with current colleagues that have informed her knowledge for using representations, specifically, informally discussing strategies with other teachers, observing her colleague's classes and paying attention to student understanding, asking for instructional advice from colleagues, and sharing resources with colleagues. These characteristics of Findlay's collaboration with current colleagues that informed her knowledge for using representations are captured in Table 13 at the end of this section (along with the other participants' descriptions).

Allie. Discussing the collaborations with current colleagues that have informed her knowledge for eliciting students ideas about energy in the beginning of the unit, Allie explained, "The questions that we developed as a team were to get, we wanted to simplify them and get kids thinking about energy." In this example, Allie reveals that one of the characteristics of her collaboration with current colleagues that informed her knowledge of using representations was developing resources (e.g., questions) as a team.

Allie also discussed her knowledge of using the *Family Guy* analogy. She explains:

> [One of the teachers on my teaching team] came up with the idea in the team meeting and we said that's really cool. You could use that character to represent something and then we just kind of talked about how we would use him for [the Feynman lecture] and she already had a vision of what she wanted to do and so she kind of shared it with us and we said yeah, you could use it for that, and we just started talking about how we would put it together and how and she came up with a lot of the structure as far as his bedroom and the system and all that kind of stuff. And then we just talked about how would we represent that? And it really was all her idea. It was really neat. And then we just kind of sat and lined it out and said what kinds of things could we accomplish with it, what could we have him do and we came up with some of the scenarios and them she put it together and we watched it and changed a few things.

In this example, reiterates the characteristic of developing resources as a team and also reveals that two additional characteristics of her collaboration with current colleagues that informed her knowledge of using representations were 1) sharing resources with colleagues and 2) discussing strategies with other teachers.

At another point, Allie reemphasized her collaborations with her teaching team. She explains, "We all kind of agree on essentials, we agree on curriculum, we agree on the activities we should be doing. We agree on resources." She explained that these collaborations included sharing videos and determining when to introduce representations (e.g. system circle). These examples reiterate the characteristics of discussing strategies and sharing resources and introduce agreeing on the goals of the unit (i.e., the essentials) as a characteristic of Allie's collaboration with current colleagues that informed her knowledge of using representations.

In these statements, Findlay reveals characteristics of her collaborations with current colleagues that have informed her knowledge for using representations, specifically, developing resources as a team, sharing resources with colleagues, discussing strategies with other teachers, and agreeing on the goals of the unit.

Taken together, the participants' statements and explanations paint a picture of the types of experiences collaborating with current colleagues that informed the participants' knowledge for using representations. These experiences are highlighted in the Table 13.

Table 13

Characteristics of the Participants' Experiences Collaborating with Their Current Colleagues that Have Contributed to Their Knowledge for Using Representations

Characteristics of Collaboration with Current Colleagues
• [2]Observing colleagues' classes and paying attention to student understanding
• [3]Informally discussing strategies with other teachers
• Asking for instructional advice from colleagues
• [2]Sharing resources with colleagues
• Developing resources (e.g., questions) as a team
• Agreeing on the goals of the unit

Note: Characteristics that are shared between two participants are indicated with a ([2]) and characteristics shared between all three participants are identified with a ([3]).

Past collaboration with experienced teachers. The source "Past Collaboration with Experienced Teachers" captures the participants' experiences as beginning teachers during which they worked with experienced teachers in their school. This source includes formal as well as informal collaborations.

Jake. Discussing past collaborations with experienced teachers that informed his knowledge of breaking ideas into basic components, Jake explains:

> I started walking into other peoples' classes. I'd always ask first. Man, I'm telling you I think that that really helped…I started to open my eyes more to here are some other strategies to try… some of the better teachers I've ever know have done that [break ideas down]…there were two in particular [gives names]. Both really good at that, just making sure that they broke it down into its most basic components.

In this example, Jake reveals that one of the characteristics of his past collaboration with experienced teachers that informed his knowledge of using representations was observing experienced teachers' instructional strategies. This characteristics of Jake's collaboration with current colleagues is captured in Table 14 at the end of this section (along with the other participants' descriptions).

Allie. Discussing past collaborations with experienced teachers that informed her knowledge using manipulatable objects (e.g., marbles), Allie explains:

> I realized that you could use manipulatives but I never really knew why. Like we had a teacher too that was really big in learning styles and she would make the flip shoots and all those things that the kids could use to learn with, just all kinds of things, like review mechanisms, where the kids would press a steel thing onto and it would if they got the right, it was like pick a hole or something and they would stick it in there and it would light up for them if it was right. Some of the stuff she made was just amazing, but it was pretty high maintenance work, but once you had it done it was done. And so I was around teachers, older teachers who used it and believed in it and I saw what they were doing and so I think that's probably where I got all of my ideas.

In this example, Allie reveals that one of the characteristics of her past collaboration with experienced teachers that informed her knowledge of using representations was observing experienced teachers' instructional strategies, specifically, observing experienced teachers who used manipulatives and believed in their effectiveness.

Taken together, the participants' statements and explanations reveal that observing experienced teachers' instructional strategies was the prominent characteristic of collaborating with experienced teacher that informed the participants' knowledge for using representations. This characteristic is highlighted in Table 14

Table 14

Characteristics of the Participants' Various Experiences that Have Contributed to Their Knowledge for Using Representations

Experience/Source	Characteristics of the Source
Past collaboration with experienced teachers	• [2]Observing experienced teachers' instructional strategies
Academic experiences as a learner of science	• Being confused by the instructional strategies used by the teachers • Feeling stupid when asked to justify ideas about topics on which one is unsure
School district expectations	• [2]The requirement that teachers align their instruction to the district final assessment • The expectation regarding the scope of the energy unit • [2]The expectation that all of the ninth grade teachers participate in the Physics First project • The expectation that the PLC stay on the same schedule • The expectation that the teachers use the Physics First curricular materials for their instruction
Collaboration with university faculty and other university professional development	• Being provided strategies to try out in class • Participating in book studies focused on student learning
Non-academic life experiences	• Strategies used in dog training transferring to strategies for teaching energy • Transferring approaches to sequencing instruction as a basketball coach to the sequencing of instruction regarding representations • Using examples in light of the references that children and students use

Note: Characteristics that are shared between two participants are indicated with a ([2]) and characteristics shared between all three participants are identified with a ([3]).

Academic experiences as a learner of science. The source "Academic Experiences as a Learner of Science" captures the participants' experiences as students in formal academic settings where the focus of the instruction was on science content. This source does not include academic experiences as a learner of science in the professional development settings described previously (e.g., Physics First).

Jake. Discussing the academic experiences as a learner of science that informed his knowledge of using sketches, Jake explains:

> A lot of these teachers would write on the board and you couldn't figure out what they were saying or what they were doing or you couldn't identify what they were exactly trying to get across. So for me it was just try to be as clear as possible.

In this example, Jake reveals that one of the characteristics of his academic experiences as a learner of science that informed his knowledge of using representations was being confused by the instructional strategies (i.e., sketches) used by the teachers.

Allie. Discussing the academic experiences as a learner of science that informed her knowledge of using student justification as a strategy, Allie explains, "I was one of those kids that I think, you know I was willing to volunteer if I knew the answer, and I was kind of confident. But if I wasn't oh please don't call on me." Allie also explains, "I think that I had teachers in my life that made me feel a little bit stupid when I had the wrong answer too, and I think that that kind of sticks with you and you think about that. It's kind of a part of your fabric…so yeah, I'm very aware of that stuff." In these examples, Allie reveals that one of the characteristics of her academic experiences as a learner of science that informed her knowledge of using representations was feeling stupid when asked to justify ideas about topics on which she was unsure.

Taken together, these statements and explanations reveal that being confused by the instructional strategies used by the teachers and feeling stupid when asked to justify ideas about topics on which one is unsure were the characteristics of the participants' academic experiences as a learner of science that informed the participants' knowledge for using representations. These characteristics are highlighted above in Table 14.

School district expectations. The source "School District Expectations" captures the participants' experiences responding to the policies, guidelines, programs, etc., imposed on them by the school district. This source does not include any voluntary experiences supported by the school district.

Jake. Discussing characteristics of the school district expectations that informed his knowledge of the types of energy that he included in the unit, Jake explains, "[As a school district] we had to come to an agreement [on the forms of energy to include] because if we were going to test on it, we had to make sure we used the same terminology." In this example, Jake reveals that one of the characteristics of the school district expectations that informed his knowledge of using representations was the requirement that teachers align their instruction to the district final assessment.

Findlay. Discussing characteristics of the school district expectations that informed her knowledge of the types of problems and questions that she included in the unit, Findlay explains, "It has to do with the district final because on the final they use a particular format and my kids didn't have experience with that format." In this example, Findlay reveals that one of the characteristics of the school district expectations that informed her knowledge of using representations was the requirement that teachers align their instruction to the district final assessment.

Findlay also explained that the energy unit only includes qualitative representations of energy because "our district has shortened it." In this example, Findlay reveals that one of the characteristics of the school district expectations that informed her knowledge of using representations was the expectation regarding the scope of the energy unit.

As a final example, Findlay discussed her decision to participate in the Physics First program, explaining:

> It got to the point where I was the only one in our department [not signed up for Physics First], it was like well maybe I'd better jump along for the ride, because I wouldn't be able just to free ride it and survive. And I'm really glad I did it.

In this example, Findlay reveals that one of the characteristics of the school district expectations that informed her knowledge of using representations was the expectation that all of the ninth grade teachers participate in the Physics First project.

Allie. Discussing the school district expectations that informed how much time she spent on the representations in the energy unit, Allie explains, "As a PLC [Professional Learning Community] school we're kind of expected to be on kind of the same schedule." In this example, Allie reveals that one of the characteristics of the school district expectations that informed her knowledge of using representations was the expectation that the PLC stay on the same schedule.

Discussing her knowledge of including the Physics First curricular materials in her instruction, Allie explains, "I felt like we were pretty much expected to do what was in Physics First and all the activities that were given to us." In this example, Allie reveals that one of the characteristics of the school district expectations that informed her knowledge of using representations was the expectation that the teachers use the Physics First curricular materials for their instruction.

Finally, discussing her decision to participate in the Physics First project, Allie explains, "I wanted to, and plus, if you wanted to be with the rest of the ninth grade group I mean obviously you had to do it because, if you wanted to keep your job in 9th grade, you jumped in there." In this example, Allie reveals that one of the characteristics of the school district expectations that informed her knowledge of using representations was the expectation that all of the ninth grade teachers participate in the Physics First project.

Taken together, the participants' statements and explanations paint a picture of the characteristics of the school districts' expectations that informed the participants' knowledge for using representations, specifically, the requirement that teachers align their instruction to the district final assessment, the expectation regarding the scope of the energy unit, the expectation that all of the ninth grade teachers participate in the Physics First project, the expectation that the PLC stay on the same schedule, and the expectation that the teachers use the Physics First curricular materials for their instruction. These experiences are highlighted above in Table 14.

Collaboration with university faculty and other university professional development. The source "Collaboration with University Faculty and Other University Professional Development" captures the participants' experiences collaborating with university faculty and participating in university-sponsored professional development. This source does not include the other professional development discussed previously (i.e., Physics First and school district-supported professional development).

Jake. Discussing some of the university collaborations that have informed his knowledge of engaging students in ideas, Jake explains:

> This professor that we were working with, who through the University found out that we were teaching this physics and engineering… came to us, and he threw out a bunch of different scenarios that he thought that we'd like to try and they were very effective.

In this example, Jake reveals that one of the characteristics of collaborating with university faculty that informed his knowledge of using representations was being provided instructional strategies to try out in his class. Jake also discussed his knowledge of having students construct understandings about energy by starting with their current understandings. He explains that he read the book *How Students Learn* when he was

> Doing stuff 10 years ago. I think it was the [Project Name] through the engineering school. We did book studies and that was neat because the more I read it the more I thought man…and that's what I'm trying to do with these kids is, you know a simple thing like energy. Something you can't see feel or touch but we all know it's there. So develop a model for what you think energy is and then we talk about what an appliance is. How is it changing this idea of energy that you have and converting it into a different idea?

In this example, Jake reveals that one of the characteristics of participating in other university professional development that informed his knowledge of using representations was participating in book studies focused on student learning.

Taken together, these statements and explanations paint a picture of the characteristics of collaboration with university faculty and other university professional development that informed the participants' knowledge for using representations These characteristics, specifically, being provided instructional strategies to try out in class and participating in book studies focused on student learning are captured above in Table 14.

Non-academic life experiences. The source "Non-Academic Life Experiences" captures the participants' life experiences outside of science teaching and learning. The source includes experiences connected to the school setting as well as experiences not connected to school settings.

Jake. Discussing the non-academic life experiences that informed his knowledge of using a dashed circle for the system circle, Jake explains, "I do a lot of dog training and they learn by association. So if this is a dashed circle and I make that little circle in the middle of the bar graphs dashed, it sure makes it easy for them to understand that this means that's the system." In this example, Jake reveals that one of the characteristics of his non-academic life experiences that informed his knowledge of using representations is the strategies that he uses in dog training transferring to his strategies for teaching energy.

At another point, Jake discussed that his knowledge of introducing the system circle early in the unit so that students are prepared for bar charts was informed by his experiences as a basketball coach. He explained that as a coach, his focus was on

> Leading [players] in the right direction, making sure that they understand, that they know why they are doing the [drills] that they do. And not necessarily knowing [the drills], but doing them so that something in the future will come back and say now I know why I did this. I'll give you a perfect example [connected to his instruction]. So, today you videotaped a class where I drew a dashed circle around the system. And I know the kids are thinking why do I have to bother circling the system. Why is it a dashed circle? So then, from there we go to the bar graphs, there's a dashed circle in the middle of the bar graphs. And then they associate the fact that that means the system. And even today, and you caught this today. Okay this is so stupid. Why do I have to draw a picture of a cart going through a loop in the middle of a dashed circle? What's the purpose of doing that? Well what they're not going to see is in Monday when I take out parts of the system and we talk about work, when I draw those parts outside the system, they're going to have to draw arrows that say the energy from this goes to this. And it's going to be really neat how everything just falls into place. And then it will make what I have to teach so much easier to understand it's ridiculous.

In this example, Jake reveals that one of the characteristics of his non-academic life experiences that informed his knowledge of using representations was transferring his approach to sequencing instruction as a basketball coach to his sequence of instruction regarding representations.

Findlay. Discussing the non-academic life experiences that informed her knowledge of using examples to facilitate student understandings of energy representations, Findlay elaborates:

> My daughter is in 10th grade and my son is in 7th. That changed the way that I teach…sometimes [her students] bring references from the outside and if I didn't have my son or daughter I wouldn't get it.

In this example, Findlay reveals that one of the characteristics of her non-academic life experiences that informed her knowledge of using representations is having children and using examples in light of the references that her children and students use.

Taken together, the participants' statements and explanations reveal characteristics of the participants' non-academic life experiences that informed their knowledge for teaching, specifically, strategies used in dog training transferring to strategies for teaching energy, transferring approaches to sequencing instruction as a basketball coach to the sequencing of instruction regarding representations, and using examples in light of the references that children and students use. These experiences are highlighted above in Table 14.

CHAPTER FIVE: DISCUSSION

The purpose of this study was to explore and identify the experiences that informed the development of veteran 9th grade physics teachers' specialized knowledge, or PCK, for using representations to teach the topics of energy transformation and transfer. The study was guided by the assumption that there are a limited number of experiences in which teachers engage throughout their career that contribute in significant ways to the development of their knowledge. The results of the analysis revealed that nine categories of experiences informed the development of the three participant's PCK for using representations to teach the energy topics. The analysis also revealed that as a result of engaging in the nine experiences, the participants developed more integrated knowledge for using representations in their instruction, which included understandings regarding the essential features of specific representations, knowledge of barriers to student learning regarding representations, and knowledge of how to help students develop understandings about specific representations. In the following section, I will discuss these findings in light of the reviewed literature. The discussion is organized around the three sub-research questions that guided the study, specifically, 1) what specialized knowledge do veteran teachers have for using representations to teach energy transformation and transfer, 2) how does knowledge change over the teacher's career, and 3) what experiences influence change in teacher knowledge?

What Specialized Knowledge Do Veteran Teachers Have for Using Representations to Teach Energy Transformation and Transfer?

The results of the analysis of the participants' current knowledge revealed that the participants possessed integrated knowledge for using representations to teach the energy topics. Specifically, each of the participants demonstrated integrated knowledge in terms of drawing from all five components of PCK when planning and implementing their instruction as well as in terms of each component of PCK informing the other four components. These findings are consistent with both the Grossman (1990) and Magnusson et al. (1999) conceptualizations of PCK in which the components of PCK are argued to behave reciprocally and as inextricably connected. Additionally, these results are consistent with the descriptions of experienced teachers' PCK as described in the reviewed literature. For example, Lee and Luft (2008) described PCK from the perspectives of four experienced secondary science teachers and concluded that the critical aspect of the teachers' knowledge was their "ability to access and emphasize the different components [of PCK] individually and simultaneously" (p. 1360). Similarly, Henze et al. (2008) explained that the experienced teachers in their study developed PCK "in such a way that the content of the different elements [of PCK] were consistently and dynamically related to each other and to the teaching of [the topic]" (p. 1339). These studies highlight the integrated nature of PCK that characterizes the instruction of experienced (and presumably expert) teachers – a characteristic shared by the participants in the present study. These similarities support the conclusion that the participants in the present study possess the same integrated PCK that is characteristic of experienced teachers as described in the literature.

The analysis of the participants' current knowledge also revealed that the participants possessed an understanding of the essential features of the selected representations that they used in their instruction. This included knowledge of deconstructing the representations into their basic components, knowledge of reconstructing the representations to address energy concepts, understandings regarding how the features of the representations related to each other, and knowledge of how the representations connected to energy concepts and ideas. These understandings mirror the types of understandings of experts as described in the literature. For example, Grosslight et al. (1991) found that experts viewed models as constructed representations that capture and help explain different theoretical perspectives. Itza-Ortiz et al. (2003) described that experts are able to differentiate between different representations and connect the representations to the physics concepts and ideas. Gardner (1991), Gilbert (2007) and Van Heuvelen and Zou (2001) all highlight that fluency and expertise in physics is characterized by an individual's ability to represent concepts in a number of ways and to move back and forth between them. The findings in the present study suggest that in terms of understanding the essential features of the selected representations and using the representations to teach the selected topics in energy, the participants demonstrated a level of expertise consistent with the descriptions of expertise found in the literature.

The analysis of the participants' current knowledge also revealed that the participants possessed an understanding of barriers to student learning regarding the specific representations that were used during their instruction. This included knowledge of student misconceptions and an awareness of student confusion connected to the representations. Additionally, the participants understood the difficulties that the students had with the instructional strategies that they used to introduce the representations, the challenges that the students faced with the curricular materials that supported the instruction, and the difficulties that the students encountered with the assessments. These findings are consistent with the findings in the literature regarding the types of student understandings and misunderstandings commonly associated with instruction that is focused on representations, including that students have misconceptions and confusion with representations (Albe et al., 2001; Beichner, 1994; Grosslight et al., 1991; Itza-Ortiz et al., 2003), that students encounter difficulties with strategies (Ambrose et al., 1999; Clement, 1993; Monaghan & Clement, 2000; Van Heuvelen & Zou, 2001), that students face challenges with the curriculum (Ambrose et al., 1999; Meltzer, 2005; Podolefsky & Finkelstein, 2006; Van Heuvelen & Zou, 2001), and that students encounter difficulties with assessment (Meltzer, 2005). Furthermore, these findings are consistent with the findings in the literature that PCK hinges on a teacher's knowledge of student difficulties. For example, Halim and Meerah (2002) correlated pre-service teachers' limited PCK to their inability to identify student misconceptions. De Jong, van Driel, and Verloop (2005) and De Jong and van Driel (2004) associated the development of pre-service teachers' PCK to their deeper understanding of their students' difficulties while Drechsler and van Driel (2008) concluded that the impact of a training course on the development of in-service teachers' PCK was limited because only a few of the teachers actually adjusted their instructional strategies and their use of models to address student difficulties. The results of the present study regarding the participants' knowledge of barriers to student learning in terms of the specific representations that they used during their instruction suggest that the participants' knowledge of barriers to student learning is consistent with well-developed PCK associated with experienced and expert teachers (as opposed to novice teachers) as described in the literature.

Finally, the analysis of the participants' current knowledge revealed that the participants possessed knowledge of how to help students develop understandings about representations. The participants accomplished this by drawing from their knowledge in all five components of PCK. For example, the participants used a wide range of instructional strategies (e.g., modeling stations, T-Chart race, video clips, simulations, challenging homework prior to explanations, interactive analogies, etc) and a variety of assessments (e.g., ABC flash cards, logical questioning, whiteboarding, etc) during their instruction. These strategies and assessments were shaped by the participants' knowledge of student understanding (e.g., students have better understandings if they come up with definitions on their own, memorizing does not promote deep understanding, etc), their knowledge of the curriculum (e.g., T-charts, pie charts and bar charts all connect to the Law of Conservation of Energy, terms are important for future representations), and their orientations (e.g., come up with the terms first based on an exploration experience, begin with a common experience, break concepts down into basic components that build on each other, introduce one idea or component at a time). These five components of PCK functioned as an integrated group to inform how the participants helped the students develop understandings about the representations, and ultimately, about the concepts of energy transformation and transfer. As discussed above, this integration is the hallmark of PCK and it distinguishes the participants from novice teachers and highlights their knowledge as being both well-developed (integrated) and consistent with experienced teachers described in the literature (although not all experienced teachers demonstrate this knowledge) in terms of their level of integration and in terms of their specialized knowledge for using representations in their instruction (Cohen & Yarden, 2009; Drechsler & van Driel, 2008; Henze et al., 2008; Lee et al., 2007).

How Does Knowledge Change Over the Teacher's Career?

The results of the analysis of the participants' current knowledge revealed that over time, the participants developed more integrated knowledge for using representations, developed understandings of the essential features of specific representations for teaching energy, developed understandings of barriers to student learning regarding specific representations, and developed knowledge of how to help students develop understandings about representations. In short, the well-developed PCK and expertise that characterizes the participants' current instruction was absent in their previous instruction. This finding is consistent with the literature on pre-service and beginning teachers. For example, Halim and Meerah (2002) reported that the pre-service teachers in their study were unable to transform their understanding of basic physics concepts to forms accessible to students. Additionally, the researchers highlighted the teachers' limited ability to identify student misconceptions or select appropriate instructional strategies. Friedrichsen et al. (2009) concluded that the prospective teachers in their study "had limited knowledge for teaching in all categories of PCK" (p. 376) while the beginning teachers in Lee et al.'s (2007) study had limited or basic levels of PCK. In short, these studies, and consequently, the findings in the present study, are consistent with Justi and van Driel's (2005) appraisal that, "For preservice or beginning science teachers, it appears that their knowledge base often consists of elements which are not integrated, and not coherently related to their actions in classroom practice" (p. 197). This suggests that over time, the participants in this study had experiences that promoted and informed the development of their knowledge for using representations from knowledge that is typical of beginning teachers to an integrated and specialized knowledge. In light of the finding that not all experienced teachers have this well-developed knowledge for using representations (Cohen & Yarden, 2009; Drechsler & van Driel, 2008; Henze et al., 2008), it is critical to consider the experiences that the participants identified as contributing to the development of their PCK.

What Experiences Influence Change in Teacher Knowledge?

The analysis of the participants' experiences that influenced change in their knowledge resulted in the identification of experiences that fell into nine categories. The nine categories were: 1) teaching experience, 2) Physics First, 3) other school district-supported professional development 4) collaboration with current colleagues, 5) past collaboration with experienced teachers, 6) academic experiences as a learner of science, 7) school district expectations, 8) collaboration with university faculty and other university professional development, and 9) non-academic life experiences. These nine categories are discussed relative to the reviewed literature. However, instead of discussing each of the categories in the order listed above, for the sake of clarity, I will discuss the prominent experiences individually while grouping the other categories by themes that correspond to the reviewed literature.

Teaching Experience

The research literature continually supports the conclusion that, in general, teaching experience represents a significant source regarding the development of a teacher's PCK (Buaraphan et al., 2007; De Jong & van Driel, 2004; De Jong et al., 2005; Lee & Luft, 2008; Shulman, 1987; van Driel et al., 1998). In this sense, it is not surprising that teaching experience emerged as one of the primary sources in the development of the participants' PCK for using representations. However, the literature is also clear that teaching experience alone is insufficient for the development of PCK. Instead, teaching experience must be coupled with reflection on one's teaching (Buaraphan et al., 2007; Friedrichsen et al., 2009; Justi & van Driel, 2005), which begs the question, was the teaching experience described by the participants supported by reflection?

Examining the characteristics of the participants' teaching experience as highlighted previously in Table 10 (and below in Table 15) suggests that reflection served as the foundation from which the participants' teaching experience informed their instruction. For example, the participants' actions were characterized by descriptors that included considering, exploring, observing, recognizing, and modifying elements of their instruction. In all of these examples, it appears that the participants' reflection served as a central feature of the specific experiences that informed the changes in the participants' instruction. That is, the participants did not just mention that the experiences occurred, but instead, they described their awareness of the experiences and demonstrated how their instruction changed in light of the experiences. Additionally, in the majority of the instances, the participants were reflecting on their interactions with students. For example, the participants focused on student confusion, student questions, student feedback, student work, and student success. This connection between reflection and changes in instruction is consistent with a constructivist perspective regarding teachers as learners who actively change understanding in light of reflecting on new experiences (Piaget, 1951, 1952; von Glasersfeld, 1995; Vygotsky, 1978; Wertsch, 1997).

Exploring the characteristics of the participants' teaching experience (below in Table 15) also reveals that the experiences from which the participants drew and reflected upon were connected to multiple components of PCK. For example, all three participants described that through their teaching experiences, they recognized student confusion during instruction and on assessments. These experiences served to inform their knowledge of student understanding. Similarly, all three participants described that through their experiences teaching the topic of energy in multiple years, they developed knowledge of common areas of student confusion. Again, this experience informed their knowledge of student understanding.

Table 15

Connections Between the Characteristics of the Participants' Teaching Experience and the Corresponding Component of PCK

Characteristics of Teaching Experience	PCK Component Informed
• [3]Recognizing student confusion during instruction and on assessments • [3]Knowing common areas of student confusion based on teaching the topic in multiple years • Knowing what kinds of questions students will ask based on teaching the topic for multiple years • Listening to student feedback regarding how much structure they want • Experiencing student resistance to learning when not engaged • Recognizing students' intolerance for repetition of strategies	Student Understanding
• [2]Breaking down instruction on representations and evaluating the success of the approaches by examining student assessments • Considering an existing instructional strategy in light of new content • Recognizing that students were not achieving the objectives of the instructional strategy in previous years' instruction	Instructional Strategies
• [2]Recognizing the better problems and examples within the curriculum after teaching the topic at least once • Spending time exploring and using technology • Making changes in the curricular materials based on identifying student confusion via student work	Curriculum

Note: Characteristics that are shared between two participants are indicated with a ([2]) and characteristics shared between all three participants are identified with a ([3]).

In contrast, the participants described that another characteristic of their teaching experience was breaking down instruction on representations and evaluating the success of the approaches by examining student assessments. These experiences served to inform their knowledge of instructional strategies (see Table 15). The participants also described that a component of their teaching experience was considering an existing instructional strategy in light of new content. Again, this experience served to inform their knowledge of instructional strategies. However, the participants also discussed that a characteristic of their teaching experience was recognizing the better problems and examples within the curriculum, after teaching the topic at least once. These experiences informed the participants' curricular knowledge. Interestingly, although the majority of the instances listed in Table 15 demonstrate that the participants were reflecting on their interactions with their students as a result of their assessments of students (primarily informal), their teaching experience did not directly inform their knowledge of assessment in terms of assessments connected to using representations to teach energy. That is, the participants used assessment strategies during their teaching experiences to develop knowledge of the other components of PCK related to using representations to teach energy, but their knowledge of assessment strategies for using representations to teach energy did not directly develop as a result of their teaching experiences.

As these examples highlight, and as demonstrated in Table 15, only three of the five components of PCK – specifically, knowledge of student understanding, knowledge of instructional strategies, and knowledge of curriculum – were informed directly by the characteristics of the participants' teaching experiences. The resulting conclusion is that the participants' knowledge of assessment and their orientation was not informed directly by their teaching experiences. In short, for the three participants in this study, reflecting on their teaching experience alone was insufficient for developing integrated PCK (i.e., integration between all five components). This conclusion supports Friedrichsen et al.'s (2009) finding that "teaching experience alone is not sufficient for building knowledge for teaching" (p. 374). However, whereas Friedrichsen et al. found that the beginning teachers in their study "lacked topic-specific knowledge about science learners [student understanding], instruction [instructional strategies], curriculum, and assessment" (p. 374), the experienced teachers in the present study demonstrated topic specific knowledge in three of the four components listed (i.e., student understanding, instructional strategies, and curriculum) in terms of using representations to teach energy. This comparison suggests that although the combination of more experience teaching plus reflection on teaching can result in the development of a teacher's topic-specific knowledge of student understanding, instructional strategies, and curriculum, having years of teaching experience plus reflection alone is inadequate for developing integrated PCK (i.e., knowledge in all five components).

Physics First

As described in the review of the literature, the development of PCK can be supported through professional development experiences aimed at in-service teachers. For example, Justi and van Driel (2005) reported on the development of beginning chemistry teachers' PCK as a result of their participation in a professional development program that focused on models and modeling. Clermont et al. (1993) concluded that in-service chemistry teachers developed PCK as a result of a workshop focused on theory, modeling, practice, and feedback as they related to the use of demonstrations in chemistry, while van Driel et al. (1998) reported that twelve experienced high school chemistry teachers developed PCK as a result of their participation in a topic-specific workshop. In contrast to these studies, Drechsler and van Driel (2008) concluded that nine experienced chemistry teachers' PCK was not strengthened after their participation in a training course that focused on student difficulties and using models to teach selected topics in chemistry. The conclusion that some PD is effective at informing the development of teacher knowledge, while some PD is not, is supported throughout the PD literature (Ball & Cohen, 1999; Birman et al., 2000; Borko, 2004; Garet et al., 2001;

Loucks-Horsley et al., 2003; Putnam & Borko, 1997; Wilson & Lowenberg, 1991), which begs the question, how did the Physics First project inform the participant's development of PCK for using representations to teach energy transformation and transfer?

Examining the characteristics of the participants' experiences with Physics First and the corresponding components of PCK (Table 16) suggests that overall, Physics First contributed to the development of the participants knowledge in only three components of PCK, specifically, knowledge of instructional strategies, knowledge of curriculum, and knowledge of assessment.

Table 16

Connections Between the Characteristics of the Participants' Experiences with Physics First and the Corresponding Component of PCK

Characteristics of Physics First	**PCK Component Informed**
• [2]Observing strategies and how they work • [2]Participating in strategies for justifying ideas • Participation in exploring an idea and then investigating what happened and why it happened • Participating in building representations • Observing the instructors as they demonstrated or modeled instructional strategies	Instructional Strategies
• [3]Being provided curricular resources • [3]Being provided ideas for representing energy concepts • Being provided possible learning objectives • Receiving new technology • Working through the curricular resources	Curriculum
• [2]Being provided strategies for assessment • Being provided with problems and questions of varying difficulty to be used for different purposes • Observing instructors model assessment strategies	Assessment

Note: Characteristics that are shared between two participants are indicated with a ([2]) and characteristics shared between all three participants are identified with a ([3]).

This finding supports that conclusion by Clermont, Krajcik, and Borko (1993) that PD can support the development of a teacher's knowledge of instructional strategies. However, Justi and van Driel (2005) and van Driel, Verloop, and de Vos (1998) found that PD can also support the development of a teacher's knowledge of student understanding. This is interesting, because in the present study, the participants' experiences in Physics First did not inform their knowledge of student understanding. These findings suggest that PD can inform the development of multiple components of PCK, but that the specific components informed differ between PD projects. Presumably, the characteristics and features of the PD project shapes the knowledge components informed by the teacher's experiences in the PD.

The review of the PD literature (Loucks-Horsley et al., 2003; National Research Council, 1996; National Staff Development Council, 2001; Park Rogers et al., 2007) highlights the following features as characteristics of effective PD: 1) demonstrating/modeling activities and teaching strategies associated with the curriculum or PD content, 2) providing teachers with the resources necessary to easily implement the curriculum or activities, 3) establishing opportunities for teachers to experience activities from a student's perspective, and 4) developing a network of support for the teachers, both with colleagues and PD facilitators. Comparing these features of effective PD to the characteristics of the Physics First project described by the participants as informing the development of their knowledge for using representations reveals a close alignment between the characteristics of Physics First and the features of effective PD. For example, the participants described that one of the characteristics of Physics First that informed the development of their PCK was that they observed the Physics First instructors as they demonstrated instructional strategies. This characteristic aligns with feature 1 of effective PD. The participants also described that one of the characteristics of Physics First that informed their knowledge of using representations was being provided curricular resources. This characteristic aligns with feature 2 of effective PD. Additionally, the participants discussed the Physics First characteristic of participating in building representations. This characteristic aligns with feature 3 of effective PD. These connections, as well as the connections between all of the characteristics of Physics First, are highlighted in Table 17.

Table 17

Comparisons of Four Features of Effective PD with Characteristics of Physics First as Described By the Participants

Features of Effective PD	**Characteristics of Physics First**
Demonstrate/model activities and teaching strategies associated with the curriculum or PD content	• [2]Observing strategies and how they work • Observing the instructors as they demonstrated or modeled instructional strategies
Provide teachers with the resources necessary to easily implement the curriculum or activities	• [3]Being provided curricular resources • [3]Being provided ideas for representing energy concepts • Being provided possible learning objectives • Receiving new technology • Being provided with problems and questions of varying difficulty to be used for different purposes • [2]Being provided strategies for assessment
Establish opportunities for teachers to experience activities from a student's perspective	• [2]Participating in strategies for justifying ideas • Participation in exploring an idea and then investigating what happened and why it happened • Participating in building representations • Working through the curricular resources
Develop a network of support for the teachers, both with colleagues and PD facilitators	• n/a

Note: Characteristics that are shared between two participants are indicated with a ([2]) and characteristics shared between all three participants are identified with a ([3]).

Viewed collectively, the characteristics of Physics First align with the first three features of effective professional development. Interestingly, feature 4 of effective PD (i.e., develop a network of support for the teachers, both with colleagues and PD facilitators) was not reflected in the characteristics of Physics First as discussed by the participants, although the establishment of professional learning communities (PLCs) was a component of the Physics First project. And as reported in the findings, the participants' experiences in their PLCs informed the development of their knowledge for using representations to teach energy. However, prior to the introduction of Physics First, the Westwood School District already operated as a PLC school. Presumably, this is the reason why the participants did not associate their experiences in their PLCs as connected to their involvement in the Physics First project.

Comparing the results of the participants' teaching experience with their experiences in Physics First reveals that the combination of the two experiences informed the development of the participants' knowledge for using representations in four PCK components (i.e. curriculum, instructional strategies, student understanding, and assessment). And although the fifth component, orientations, does not have a direct connection to the characteristics of the participants' teaching experience and their experience in the Physics First project, it appears that the orientation component was informed indirectly by these experiences. For example, all three participants demonstrated orientations regarding the teacher's role in breaking complex science ideas into basic components. And although a single characteristic of their teaching experience, or their experience in Physics First, did not inform this orientation, it is evident how their experiences breaking down instruction on representations and recognizing student confusion during instruction and on assessments as well as their experience in Physics First of building representations as a participant informed this orientation. Similar findings are evident throughout the analysis. The resulting conclusion is that that participants' orientations were informed indirectly by a combination of experiences throughout their careers.

Collaboration with Current Colleagues

As discussed previously, all of the 9th grade physics teachers in the Westwood School District collaborate together in professional learning communities (PLCs), and worked in PLCs prior to the introduction of Physics First to the district. Consequently, it is difficult to determine which characteristics of their collaborations with their current colleagues resulted from their involvement in Physics First, which of the characteristics of their collaborations were the result of the PLC culture that existed previously in their school, and which of the collaborations occurred independently of the PLC. Regardless, exploring the connection between the characteristics of the participants' collaboration with current colleagues reveals that their collaborations informed three components of their PCK regarding their knowledge of using representations to teach energy, specifically, their knowledge of instructional strategies, knowledge of curriculum, and knowledge of student understanding. These connections are highlighted in Table 18.

Table 18

Connections Between the Characteristics of the Participants' Collaboration with Current Colleagues and the Corresponding Component of PCK

Characteristics Collaboration with Current Colleagues	**PCK Component Informed**
• [3]Informally discussing strategies with other teachers • Asking for instructional advice from colleagues	Instructional Strategies
• [2]Sharing resources with colleagues • Developing resources (e.g., questions) as a team • Agreeing on the goals of the unit	Curriculum
• [2]Observing colleagues' classes and paying attention to student understanding	Student Understanding

Note: Characteristics that are shared between two participants are indicated with a ([2]) and characteristics shared between all three participants are identified with a ([3]).

The resulting conclusion, that collaboration with current colleagues can support the development of a teacher's knowledge, is demonstrated throughout the induction literature (Gold, 1996; Huling-Austin, 1990, 1992). Similarly, the influence of collaboration with colleagues is consistent with the fourth characteristic of effective PD as described above. And although it is unclear which of the characteristics of the participants' collaborations with colleagues were the direct result of the Physics First project, it is clear that the collaborations supported the participants' PD experiences. Specifically, in terms of the three participants in the study, collaboration with colleagues added a fourth component to their PCK for using representations to teach energy, namely, knowledge of student understanding. These findings suggest that with the addition of collaboration with colleagues, Physics First informed the development of the participants' knowledge for using representations in all five components of PCK.

Other School District-Supported Professional Development, Past Collaboration with Experienced Teachers, and Collaboration with University Faculty and Other University Professional Development

The findings discussed above suggest that the combination of teaching experience, the Physics First PD project, and collaboration with current colleagues contributed significantly to the development of the participants' integrated PCK for using representations to teach the topics of energy transformation and transfer. However, the participants also participated in school district-supported professional development beyond Physics First and had collaborations beyond their PLC and current colleagues. How did these experiences contribute to the participants' knowledge for using representations to teach energy? Table 19 highlights the connection between the characteristics of these other collaborations and PD experiences and the corresponding components of PCK.

Table 19

Connections Between the Characteristics of Other School District-Supported Professional Development, Past Collaboration with Experienced Teachers, and Collaboration with University Faculty and Other University Professional Development and the Corresponding Component of PCK

Experience or Source	**Characteristics of Source**	**PCK Component Informed**
Other school district-supported professional development	• Visiting different facilities and making practical connections to science • Professionals providing programs, activities, and resources connected to energy • Having easy access to professionals for questions • Being provided a break from teaching to work on literacy training with a colleague	Instructional strategies
	• Working with a team to examine the goals of the school in light of the energy unit • Professionals providing programs, activities, and resources connected to energy	Curriculum
	• Being provided training connected to how students learn in different ways • Observing model schools that focus on accounting for differences in students • Listening to an expert speak about the differences between students	Student understanding
Past collaboration with experienced teachers	• [2]Observing experienced teachers' instructional strategies	Instructional strategies
Collaboration with university faculty and other university professional development	• Being provided instructional strategies to try out in class	Instructional strategies
	• Participating in book studies focused on student learning	Student understanding

Note: Characteristics that are shared between two participants are indicated with a ([2]).

Collectively viewing the connections between the participants' experiences and the components of PCK highlighted in Table 19 reveals that the participants' other PD experiences and collaborations informed their knowledge in three components of PCK, specifically, instructional strategies, curriculum, and student understanding. The finding that collaborating with experienced teachers and university faculty can result in the development of knowledge for teaching is consistent with the literature. For example, Luft et al. (2003) concluded that the beginning teachers in their study developed knowledge for teaching as a result of their experiences in an induction program that included access to experienced secondary science teachers and observation and feedback from science faculty.

However, taken together, the participants' other PD experiences and collaborations did not result in the development of integrated PCK. In short, without teaching experience, Physics First, and current collaborations, the participants' other collaborations and PD experiences would not have resulted in the development of integrated PCK for using representations to teach energy.

School District Expectations, Academic Experiences as a Learner of Science, and Non-Academic Life Experiences

The final three experiences identified in the outcome space as contributing to the participants' knowledge of using representations to teach energy are school district expectations, academic experiences as a learner of science, and non-academic life experiences. Table 20 highlights the connection between these experiences and the corresponding PCK components that they inform.

Table 20

Connections Between the Characteristics of School District Expectations, Academic Experiences As a Learner of Science, and Non-Academic Life Experiences and the Corresponding Component of PCK

Experience or Source	**Characteristics of Source**	**PCK Component Informed**
School district expectations	• [2]The requirement that teachers align their instruction to the district final assessment • The expectation regarding the scope of the energy unit • [2]The expectation that all of the ninth grade teachers participate in the Physics First project • The expectation that the PLC stay on the same schedule • The expectation that the teachers use the Physics First curricular materials for their instruction	Curriculum
Academic experiences as a learner of science	• Being confused by the instructional strategies used by the teachers • Feeling stupid when asked to justify ideas about topics on which one is unsure	Instructional strategies
Non-academic life experiences	• Strategies used in dog training transferring to strategies for teaching energy • Transferring approaches to sequencing instruction as a basketball coach to the sequencing of instruction regarding representations • Using examples in light of the references that children and students use	Instructional strategies

Note: Characteristics that are shared between two participants are indicated with a ([2])

Together, these three experiences only informed the development of the participants' knowledge for using representations in two components of PCK, specifically, knowledge of curriculum and knowledge of instructional strategies. Interestingly, the school district expectations only informed the participants' curricular knowledge while the experiences as a learner and non-academic experiences only informed the participants' knowledge of instructional strategies. This finding is significant in terms of the school districts' influence over the participants' choice of curriculum, implementation of the curriculum, and most notably, the school districts' influence in terms of the teachers participating in the Physics First project. As discussed above, the participants' experiences in the Physics First project significantly informed the development of their PCK for using representations. Consequently, the school district played a substantial, albeit indirect, role in informing the development of the participants' PCK.

In terms of the participants' academic experiences as a learner, or their "apprenticeship of observation" (Lortie, 1975), the results are consistent with the reviewed literature. Specifically, experiences as a learner are thought to inform a teachers' general teaching knowledge, but not their PCK (Grossman, 1990). This general knowledge development is evident in that the participants only developed knowledge of instructional strategies as a result of their experiences as learners. Similarly, the participants non-academic life experiences only informed a small slice of their PCK.

What Is Missing From the List?

As discussed throughout the findings and this discussion, the following experiences informed the participants' PCK for using representations to teach energy: 1) teaching experience, 2) Physics First, 3) other school district-supported professional development 4) collaboration with current colleagues, 5) past collaboration with experienced teachers, 6) academic experiences as a learner of science, 7) school district expectations, 8) collaboration with university faculty and other university professional development, and 9) non-academic life experiences. And although these nine experiences contributed to the teacher's PCK in varying degrees, they all contributed.

But what about the sources and experiences discussed in the literature that are not included in the outcome space?

For example, a large portion of the literature on the development of teachers' PCK focuses on the influence of pre-service instruction (e.g., methods courses) on the development of teachers' knowledge (Halim & Meerah, 2002; van Driel et al., 2002; Veal et al., 1998). Additionally, the literature highlights repeatedly the potential impact of experiences such as mentoring, professional conferences, and graduate courses on the development of teacher knowledge (Huling-Austin, 1992; Luft & Patterson, 2002; Smith & Ingersoll, 2004). As described in the participant profiles in chapter 3, all three participants were involved in these types of experiences throughout their careers. So why were these not included in the outcome space? I suggest that at least two answers are possible.

First, as described in the review of the literature, the different supports and PD opportunities available to teachers throughout their careers differ in their features. As the PD literature indicates, the presence of certain features can promote the development of teacher knowledge, while the absence of these features results in the experiences having less impact on the development of teacher knowledge. Similarly, pre-service teacher methods courses differ in their features and structure. Consequently, it is possible that the experiences not included in the outcome space lacked specific features that contribute to the development of PCK for using representations to teach energy (including a lack of instruction focused on the topic of energy).

A second possible answer to the question of why additional sources were not included in the outcome space is the time period between my observation of the participants' instruction and their experiences. Specifically, the participants' experiences in their methods courses and in their experiences associated with induction occurred at the beginning of their teaching career. Over time, it is likely that memories of specific details regarding what they learned in their methods courses and in their induction experiences begin to fade or blur with other experiences. Consequently, it may be difficult for the participants to recall exactly how the methods courses informed their knowledge. However, because the purpose of a phenomenographic study is to explore the participants' conceptions of significant experiences, from the perspective of the participants, items not included in the outcome space were not significant in the development of their knowledge.

Contributions to the Literature

The above discussion highlights the ways in which this study informs and supports the reviewed literature. Additionally, the discussion highlights the ways in which the present study addresses gaps in the literature. The contribution of this study to the literature is most pronounced in three ways. First, throughout the induction, PD, and PCK literature, it is unclear what experiences help teachers transform the knowledge that they have for using representations into integrated PCK for teaching specific topics and concepts. Instead, the existing studies on the development of PCK speak to the influence of specific experiences on the development of selected components of PCK. For example, van Driel et al. (1998) reported on a PD workshop that informed the development of the participants' knowledge of student understanding and their knowledge of instructional strategies. Similarly, Justi and van Driel (2005) reported that teachers' participation in a PD program in conjunction with institutional meetings informed the development of their knowledge of student understanding and their knowledge of instructional strategies. In contrast to these studies, this present study is unique in that it identifies specific experiences and sources (e.g., reflection on teaching experience combined with professional development and collaboration) that inform the development of integrated PCK – that is, the development of knowledge in all five components of PCK. These findings help to bring greater specificity and clarity regarding the types of experiences that promote the development of integrated PCK for using representations.

Second, the literature on the development of PCK regarding representations is silent in regards to physics education. Instead, the bulk of the research on PCK and representations is focused on chemistry education (e.g., van Driel et al., 2002; van Driel et al., 1998). Consequently, this study serves as a starting point from which to explore further the development of PCK for using representations in physics instruction.

Third, both the PCK literature and physics representation literature are void of empirical studies exploring the connection between long-term PD programs (i.e., longer than one year) and the development of experienced science teacher PCK. This study fills that gap by highlighting the connection between long-term PD (e.g., Physics First) and the development of PCK and by identifying features of long-term PD that inform the development of science teacher PCK.

Conclusions and Implications

This study was guided by the overarching research question, through what experiences do veteran 9th grade physics teachers develop specialized knowledge for using representations to teach the topic of energy transformation? The results of the analysis revealed that nine categories of experiences informed the development of the three participant's PCK for using representations to teach the energy topics. This knowledge included understandings regarding the essential features of specific representations, knowledge of barriers to student learning regarding representations, and knowledge of how to help students develop understandings about specific representations. However, the nine experiences differed in terms of their contributions to the development of the participants' PCK. Specifically, the participants' teaching experiences, coupled with their experiences in the Physics First PD project and their collaborations with their colleagues, contributed most significantly to the development of their integrated PCK for using representations to teach energy transformation and transfer. Furthermore, the analysis provided support for the direct connection between the participants' experiences and their knowledge development in all of the components of PCK except orientations. It appears that the participants' orientations were shaped indirectly through multiple elements of multiple experiences. These findings have implications for pre-service teacher preparation programs, induction programs, and in-service teacher PD.

Implications for Pre-Service Teacher Education Programs

The review of the literature on the impact of pre-service teacher education programs on the development of teachers' PCK revealed that participation in methods courses does not necessarily result in the development of PCK. If PCK represents the most powerful form of knowledge for teaching, and consequently the most significant form of knowledge for impacting student learning, then the goal of teacher education programs should be to help teachers develop this knowledge as quickly as possible.

Because the features of a teacher preparation program inform its effectiveness in facilitating the development of PCK, I provide three implications regarding pre-service teacher education programs.

First, the findings highlight the importance of teaching experience on the development of PCK. Consequently, teacher preparation programs that incorporate teaching experiences are more likely to support the development of PCK. Specifically, teaching experiences that provide opportunities for teachers to reflect on their experiences with students that correspond to all five components of PCK are more likely to support the development of PCK.

Second, the findings highlight the potential for professional development that provides topic-specific instruction in terms of content and pedagogy to inform the development of PCK. Because PCK represents specific knowledge for teaching specific topics, then teacher preparation programs would benefit from integrating general teaching competencies with topic-specific instruction. In terms of methods courses, this would include exploring all of the topics that a teacher will teach in a given subject in light of the components of PCK.

Third, the results of this study suggest that teaching orientations are informed indirectly by multiple sources. Consequently, it is important that pre-service teacher preparation programs incorporate multiple opportunities for teachers to reflect upon their orientations in light of new experiences and understandings.

Implications for Induction Programs and PD

During their induction years, beginning teachers are provided a variety of supports that include collaboration with colleagues, mentoring, collaborations with school district and university teacher educators, workshops and seminars, classroom observations and feedback, conference attendance, access to experienced science teachers, graduate courses, and access to curricular resources. Throughout their careers, teachers engage in a variety of PD experiences including seminars, workshops, conferences, and small- and large-scale professional development projects. The results of this study suggest that these supports do not contribute equally to the development of teacher PCK. Considering these types of induction supports and PD experiences in light of the findings of this study, I provide four implications.

First, the participants engaged in a variety PD experiences throughout their careers. However, Physics First represented the most significant contribution to the development of their knowledge for using representations to teach energy. Like the recommendation for pre-service teacher preparation, PD programs that incorporate teaching experiences that provide opportunities for teachers to reflect on their experiences with students that correspond to all five components of PCK are more likely to support the development of PCK.

Second, and again, similar to the implication for pre-service teacher preparation, PD programs would benefit from integrating general teaching competencies with topic-specific instruction, including exploring all of the topics that a teacher will teach in a given subject in light of the components of PCK. The features of the Physics First project informed the development of the participants' knowledge in all of the components of PCK except knowledge of student understanding. The participants developed this knowledge, in part, through their collaborations with their colleagues. It is consequently important for PD designers and providers to consider how their PD provides opportunities for teachers to reflect on their topic-specific knowledge in light of all components of PCK.

Third, the literature on induction suggests that school district support is essential for an effective induction program. The teachers in the present study participated in Physics First as a result of expectations placed on them by the school district. Furthermore, the participants collaborated in PLCs as a result of school district expectations. Consequently, it is critical that school districts recognize that they can play a significant role in supporting the development of a teacher's PCK. In terms of the types of support that school districts provide, the findings of this study suggest that long-term, topic-specific PD that provides support throughout the school year can have a significant impact on the development of teacher knowledge.

Finally, the induction literature consistently provides recommendations for supporting beginning teachers through mentoring and instructional coaching. For the participants in this study, their experiences with mentors and instructional coaches did not have a direct impact on the development of their PCK. Instead, their experiences with mentors and coaches served to inform their general teaching practice (e.g., classroom management). And although the development of general teaching practice is critical for beginning teachers, I suggest that the role of mentors and coaches can be expanded to include support for the development of PCK. Like the recommendations above, this might include critical reflection on topic-specific instruction regarding all five components of PCK.

Future Research

This study explored the experiences of three veteran 9th grade physics teachers and the impact of those experiences on the development of their PCK for using representations to teach the topic of energy transformation. The analysis revealed that all three teachers entered the teaching profession with limited PCK for using representations to teach energy, but as a result of nine types of experiences, they developed integrated PCK for using representations to teach the energy topics. These findings lead to suggestions for future research.

First, this study focused on three teachers in a single school district. Conducting a similar investigation with multiple teachers in multiple school districts would provide insight into the generalizability of the findings. Specifically, expanding the pool of participants would provide additional support for the inclusion or exclusion of experiences identified in the outcome space. Are the nine experiences in the outcome space consistently included by all teachers? Are some of the experiences unique to the teachers in this school district? A study with a larger pool of participants could help answer these questions.

Second, this study focused on a single topic of instruction. Repeating the study on a different topic (e.g., uniform motion) with the same participants would inform the findings in terms of the experiences that are unique to the development of knowledge for teaching specific topics. Does the development of knowledge for using representations to teach energy differ from the development of knowledge for using representations to teach uniform motion? If so, how? These questions could be addressed by exploring other topics.

Third, the data in this study were based, in large part, upon participant recollection. Another approach would be to collect longitudinal data from participants at multiple stages in their careers. Comparing the results of a longitudinal study to the results of the present study would provide insight into both the findings as well as phenomenography as a methodological approach for exploring teacher experience. Is there a difference in the findings? What does a longitudinal study add? Are different sources more influential and different points in a teacher's career? Longitudinal studies could address these types of questions.

Finally, this study demonstrates the usefulness of the Magnusson et al. (1999) model of PCK as a tool for understanding and describing teacher knowledge. Specifically, the Magnusson et al. model is useful as a tool for showing the integrated and interconnected nature of a teacher's different types of knowledge. Furthermore, the Magnusson et al. PCK model conceptualizes the orientations component as uniquely informing and shaping the other four components. That is, although the other four components may, or may not, inform each other, orientations are conceptualized as informing all of the PCK components. Consequently, the unique position of orientations had an interesting influence on this study. Specifically, whereas there were typically clear and direct links between the participants' experiences and their knowledge of curriculum, students, assessment, and instructional strategies, in terms of orientations, the connections were more indirect. Consequently, additional research exploring the experiences and sources informing the development of orientations specific for using representations would help build the research communities' understanding regarding the indirect (and possibly direct?) links between experience and orientation.

Epilogue

The purpose of this study was to chronicle the stories of three 9th grade physics teachers in terms of the development of their knowledge. Throughout these pages, we have seen that the teachers' stories have been informed, in large part, by their interactions with other people – specifically, interactions with colleagues, students, college faculty, and administrators. These interactions have shaped the ways in which the teachers view the world of physics education and their role within that world.

Behind the scenes, however, another story regarding the development of knowledge has paralleled the story of these three teachers, namely, the story of the development of my knowledge for teaching and learning. Like the teachers in this study, the development of my knowledge has been informed primarily through my interactions with other people – specifically, interactions with my colleagues, my advisor, my committee, my instructors, my friends, and in a very significant way, my interactions with the teachers in this study. The process of observing, interviewing, and interacting with the participants in this study, and considering their ideas in light of conversations with my colleagues, advisor, and committee, have transformed how I view physics education.

As discussed in chapter one, my journey towards becoming a physics educator started with my experiences as a high school student. As a high school student, I viewed teaching and learning simplistically; teaching as telling and learning as listening. As a college student, this view of teaching and learning broadened to include teaching as telling in exciting and dynamic ways and learning as listening with enjoyment. I carried these views into my experiences as a beginning teacher and discovered them to be in error. Teaching was not just telling, and learning was not just listening. The result of five years of graduate school, culminating with this dissertation, has been the complete transformation of my views of teaching and learning. Teaching is far from the simple act of telling that I once thought, and learning is far from the simple act of listening. Instead, effective physics instruction values the student as an active constructor of knowledge, not the passive recipient of knowledge. Additionally, effective physics instruction values the teacher as a facilitator of student understanding, not the ultimate provider of knowledge. These views on teaching and learning stand in stark contrast to my previous understandings, and have transformed all that I do regarding teaching and learning. However, I have not revisited the physics classroom as a teacher. If I were to reenter the high school physics classroom as a teacher, I wonder, would my knowledge and practice mirror the integrated knowledge and practice of my participants? I believe it would. Ultimately, that appraisal would best be left for someone else to explore. And should someone study the experiences and sources contributing to the development of my PCK, one thing is certain – they would find that graduate school, and writing this dissertation, would appear at the top of the list.

This material is based upon work supported by the National Science Foundation under Grant No. 0553929. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation

REFERENCES

Abell, S. K. (2006). Researching science and mathematics teacher learning in alternative certification models. University of Missouri: National Science Foundation.

Abell, S. K. (2007). Research on science teacher knowledge. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 1105-1149). Mahwah, NJ: Lawrence Erlbaum.

Abell, S. K. (2008). Twenty years later: Does pedagogical content knowledge remain a useful idea? *International Journal of Science Education, 30*, 1405-1416.

Adams, P. E., & Krockover, G. H. (1997). Beginning science teacher cognition and its origins in the preservice secondary teacher program. *Journal of Research in Science Teaching, 34*, 633-653.

Åkerlind, G. (2002). *Principles and practice in phenomenographic research*. Paper presented at the Current Issues in Phenomenography Conference, Canberra, ACT.

Albe, V., Venturini, P., & Lascours, J. (2001). Electromagnetic concepts in mathematical representation of physics. *Journal of Science Education and Technology, 10*, 197-203.

Ambrose, B. S., Heron, P. R. L., Vokos, S., & McDermott, L. C. (1999). Student understanding of light as an electromagnetic wave: Relating the formalism to physical phenomena. *American Journal of Physics, 67*, 891-898.

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

Arhar, J. M., & Crowe, A. R. (2002). Transformational possibilities and complexities. In V. A. Anfara, L. L. Bucki & S. L. Stacki (Eds.), *Middle school curriculum, instruction, and assessment*. Greenwich: Information Age Publishing.

Ball, D. L., & Cohen, D. K. (1999). Developing practice, developing practitioners: Toward a practice-based theory of professional education. In L. Darling-Hammond & G. Sykes (Eds.), *Teaching as the learning profession* (pp. 3-31). San Francisco, CA: Jossey-Bass.

Beach, R., & Pearson, D. (1998). Changes in preservice teachers' perceptions of conflicts and tensions. *Teaching and Teacher Education, 14*, 337-351.

Beichner, R. J. (1994). Testing student interpretation of kinematics graphs. *American Journal of Physics, 62*, 750-762.

Birman, B. F., Desimone, L. M., & Porter, A. C. (2000). Designing professional development that works. *Educational Leadership, 57*, 28-33.

Borko, H. (2004). Professional development and teacher learning: Mapping the terrain. *Educational Researcher, 33*, 3-15.

Britton, E. D. (2006). Mentoring in the induction systems of five countries: A sum greater than its parts. In C. Cullingford (Ed.), *Mentoring in education: An international perspective* (pp. 107-120). Burlington: Ashgate Publishing Limited.

Brookhart, S. M., & Freeman, D. J. (1992). Characteristics of entering teacher candidates. *Review of Educational Research, 62*, 37-60.

Buaraphan, K., Vantipa, R., Srisukvatananan, P., Singh, P., Forret, M., & Taylor, I. (2007). The development and exploration of preservice physics teachers' pedagogical content knowledge: From a methods course to teaching practice. *Kasetsart Journal (Social Science), 28*, 276-287.

Bybee, R. W. (1997). *Achieving scientific literacy: From purposes to practices*. Portsmouth, NH: Heinemann.

Clement, J. (1988). Observed methods for generating analogies in scientific problem solving. *Cognitive Science, 12*, 563-586.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching, 30*, 1241-1257.

Clermont, C. P., Krajcik, J., & Borko, H. (1993). The influence of an intensive in-service workshop on pedagogical content knowledge growth among novice chemical demonstrators. *Journal of Research in Science Teaching, 30*, 21-43.

Cochran, K. F., DeRuiter, J. A., & King, R. A. (1993). Pedagogical content knowing: An integrative model for teacher preparation. *Journal of Teacher Education 44*, 263-272.

Cohen, R., & Yarden, A. (2009). Experienced junior-high-school teachers' PCK in light of a curriculum change: "The cell is to be studied longitudinally". *Research in Science Education, 39*, 131-155.

Cope, C. (2004). Ensuring validity and reliability in phenomenographic research using the analytical framework of a structure of awareness. *Qualitative Research Journal, 4*, 5-18.

De Jong, O., & van Driel, J. (2004). Exploring the development of student teachers' PCK of the multiple meanings of chemistry topics. *International Journal of Science and Mathematics Education, 2*, 477-491.

De Jong, O., van Driel, J., & Verloop, N. (2005). Preservice teachers' pedagogical content knowledge of using particle models in teaching chemistry. *Journal of Research in Science Teaching, 42*, 947-964.

Denzin, N. K., & Lincoln, Y. S. (Eds.). (2005). *Handbook of qualitative research* (3rd ed.). Thousand Oaks, CA: Sage Publications, Inc.

Desimone, L. M., Porter, A. C., Garet, M. S., Yoon, K. S., & Birman, B. F. (2002). Effects of professional development on teachers' instruction: Results from a three-year longitudinal study. *Educational Evaluation and Policy Analysis, 24*, 81-112.

Donovan, M. S., & Bransford, J. D. (2005). *How students learn science in the classroom*. Washington, D.C.: National Academy Press.

Drechsler, M., & van Driel, J. (2008). Experienced teachers' pedagogical content knowledge of teaching acid-base chemistry. *Research in Science Education, 38*, 611-631.

DuFour, R. (2004). What is a "professional learning community"? *Educational Leadership, 61*, 6-11.

Edwards, J. L. (1993). The effect of cognitive coaching on the conceptual development and reflective thinking of first year teachers. *Dissertation Abstracts International, 40*(12).

Edwards, J. L., Green, K. E., Lyons, C. A., Rogers, M. S., & Swords, M. (1998). *The effects of cognitive coaching and non-verbal classroom management on teacher* *efficacy and perceptions of school culture*. Paper presented at the Annual Meeting of the American Educational Research Association, San Diego.

Eick, C. J. (2002). Job sharing thier first year: A narrative of two partnered teachers' induction into middle school science teaching. *Teaching and Teacher Education, 18*, 887-904.

Feynman, R. P. (1994). Six easy pieces lecture 4: Conservation of Energy, October 6, 1961 [Audio recording]. Boston, MA: Addison-Wesley Publishing Company.

Fishman, B. J., Marx, R. W., Best, S., & Tal, R. T. (2003). Linking teacher and student learning to improve professional development in systemic reform. *Teaching and Teacher Education, 19*, 643-658.

Friedrichsen, P., Abell, S. K., Pareja, E., Brown, P., Lankford, D., & Volkmann, M. (2009). Does teaching experience matter? Examining biology teachers' prior knowledge for teaching in an alternative certification program. *Journal of Research in Science Teaching, 46*, 357-383.

Friedrichsen, P., Lankford, D., Brown, P., Pareja, E., Volkmann, M., & Abell, S. K. (2007, April). *The PCK of future science teachers in an alternative certification program*. Paper presented at the the annual meeting of the National Association for Research in Science Teaching, New Orleans, LA.

Friedrichsen, P., van Driel, J., & Abell, S. K. (2010). Taking a closer look at science teaching orientations [Electronic Version]. *Science Education*, 1-19,

Fuller, F. F. (1969). Concerns of teachers: A developmental conceptualization. *American Educational Research Journal, 6*, 207-226.

Fuller, F. F., & Bown, O. H. (1975). Becoming a teacher. In *Teacher Education 74th Yearbook of the National Society for the Study of Education* (pp. 25-52). Chicago: National Society for the Study of Education.

Gardner, H. (1991). *The unschooled mind*. New York: BasicBooks.

Garet, M. S., Porter, A. C., Desimone, L. M., Birman, B. F., & Yoon, K. S. (2001). What makes professional development effective? Analysis of a national sample of teachers. *American Educational Research Journal, 38*, 915-945.

Gibbs, G., Morgan, A., & Taylor, E. (1984). The world of the learner. In F. Marton, D. Hounsell & N. Entwistle (Eds.), *The experience of learning* (pp. 165-188). Edinburgh: Scottish Academic Press.

Gilbert, J. K. (2007). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 9-28). New York, NY: Springer.

Glesne, C. (1999). *Becoming qualitative researchers: An introduction*. NY: Wesley Longman, Inc.

Gold, Y. (1996). Beginning teacher support: Attrition, mentoring, and induction. In J. Sikula, T. J. Buttery & E. Guyton (Eds.), *Handbook of research on teacher education* (2nd ed., pp. 548-616). New York: Macmillan.

Goldin, G., & Shteingold, N. (2001). Systems of representations and the development of mathematical concepts. In A. A. Cuoco & F. R. Curcio (Eds.), *The roles of representation in school mathematics* (pp. 1-23). Reston, VA: National Council of Teachers of Mathematics.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*, 799-822.

Grossman, P. L. (1990). *The making of a teacher: Teacher knowledge and teacher education*. New York: Teachers College Press.

Halim, L., & Meerah, S. (2002). Science trainee teachers' pedagogical content knowledge and its influence on physics teaching. *Research in Science and Technological Education, 20*, 215-225.

Hatch, J. A. (2002). *Doing qualitative research in education settings*. Albany, NY: State University of New York Press.

Henze, I., van Driel, J., & Verloop, N. (2008). Development of experienced science teachers' pedagogical content knowledge of models of the solar system and the universe. *International Journal of Science Education, 30*, 1321-1342.

Houston, W. R. (1983). Teacher education programs. In H. E. Mitzel (Ed.), *Encyclopedia of educational research* (5th ed., pp. 1881-1891). New York: The Free Press.

Huling-Austin, L. (1990). Teacher induction programs and internships. In W. R. Houston (Ed.), *Handbook of research on teacher education: A project of the association of teacher educators*. New York: Macmillan Publishing Co.

Huling-Austin, L. (1992). Research on learning to teach. *Journal of Teacher Education, 43*, 173-180.

Husserl, E. (1931). *Ideas: General introduction to pure phenomenology* (W. R. B. Gibson, Trans.). London: George Allen and Unwin.

Ingersoll, R., & Kralik, J. M. (2004). The impact of mentoring on teacher retention: What the research says. *ECS Research Review*.

Itza-Ortiz, S. F., Rebello, N. S., Zollman, D. A., & Rodriguez-Achach, M. (2003). The vocabulary of introductory physics and its implications for learning physics. *The Physics Teacher, 41*, 330-336.

Jonson, K. F. (2002). *Being an effective mentor*. Thousand Oaks: Corwin Press.

Justi, R., & van Driel, J. (2005). A case study of the development of a beginning chemistry teacher's knowledge about models and modelling. *Research in Science Education, 35*, 197-219.

Kilpatrick, J., Swafford, J., & Findell, B. (Eds.). (2001). *Adding it up: Helping children learn mathematics*. Washington, DC: National Academy Press.

Kosztin, D., & de la Paz, G. (2005). Unit 6: Energy. Unpublished Professional Development Curriculum. A TIME for Physics First, University of Missouri.

Lee, E., Brown, M. N., Luft, J. A., & Roehrig, G. H. (2007). Assessing beginning secondary science teachers' PCK: Pilot year results. *School Science and Mathematics, 107*, 52-60.

Lee, E., & Luft, J. A. (2008). Experienced secondary science teachers' representation of pedagogical content knowledge. *International Journal of Science Education, 30*, 1343-1363.

Lesh, R., Post, T., & Behr, M. (1987). Representations and translations among representations in mathematics learning and problem solving. In C. Janvier (Ed.), *Problems of representations in the teaching and learning of mathematics* (pp. 33-40). Hillsdale, NJ: Lawrence Erlbaum.

Lewis, C. C. (2002). *Lesson study: A handbook of teacher-led instructional change*. Philadelphia, PA: Research for Better Schools, Inc.

Lortie, D. C. (1975). *Schoolteacher: A sociological study*. Chicago, IL: The University of Chicago Press.

Loucks-Horsley, S., Love, N., Stiles, K. E., Mundry, S., & Hewson, P. W. (2003). *Designing professional development for teachers of science and mathematics*. Thousand Oaks: Corwin.

Loughran, J. J. (2007). Science teacher as learner. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of Research on Science Education* (pp. 1043-1065). Mahwah, NJ: Lawrence Erlbaum Associates.

Luft, J. A., & Patterson, N. C. (2002). Bridging the gap: Supporting beginning science teachers. *Journal of Science Teacher Education, 13*, 267-282.

Luft, J. A., Roehrig, G. H., & Patterson, N. C. (2003). Contrasting landscapes: A comparison of the impact of different induction programs on teachers' practicesand beliefs. *Journal of Research in Science Teaching, 40*, 77-97.

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of PCK for science teaching. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge*. Dordrecht: Kluwer Publishing.

Martin, E., & Ramsden, P. (1987). Learning skills, or skill in learning? In J. T. E. Richardson, M. W. Eysenck & D. W. Piper (Eds.), *Student learning: Research in education and cognitive psychology* (pp. 155-167). Milton Keyes, U.K.: Society for Research into Higher Education & Open University Press.

Marton, F. (1978). *Describing conceptions of the world around us* (No. 66). Mölndal, Sweden: University of Göteborg, Institute of Educationo. Document Number)

Marton, F. (1981). Phenomenography: Describing conceptions of the world around us. *Instructional Science, 10*, 177-200.

Marton, F. (1986). Phenomenography: A research approach to investigating different understandings of reality. *Journal of Thought, 21*, 28-49.

Marton, F. (1988). Phenomenography: Exploring different conceptions of reality. In D. M. Fetterman (Ed.), *Qualitative approaches to evaluation in education: The silent scientific revolution* (pp. 176-205). New York: Praeger.

Marton, F. (1994). Phenomenography. In T. Husen & T. N. Postlethwaite (Eds.), *The international encyclopedia of education* (2nd ed., Vol. 8, pp. 4424-4429). Oxford, U.K.: Pergamon.

Marton, F., & Booth, S. (1996). The learner's experience of learning. In D. R. Olson & N. Torrance (Eds.), *The handbook of education and human development: New models of learning, teaching and schooling* (pp. 534-564). Cambridge, MA: Blackwell.

Marton, F., & Booth, S. (1997). *Learning and awareness*. Mahwah, NJ: Erlbaum.

Marton, F., & Neuman, D. (1989). Constructivism and constitutionalism: Some implications for elementary mathematics education. *Scandinavian Journal of Educational Research, 33*, 35-46.

Marton, F., & Saljo, R. (1984). Approaches to learning. In F. Marton, D. Hounsell & N. Entwistle (Eds.), *The experience of learning* (pp. 36-55). Edinburgh: Scottish Academic Press.

Meltzer, D. E. (2005). Relation between students' problem-solving performance and representational format. *American Journal of Physics, 73*, 463-478.

Missouri Department of Elementary and Secondary Education. (2007). *District profile V* (No. PS026PE). Columbia, MOo. Document Number)

Moir, E., & Gless, J. (2001). Quality induction: An investment in teachers. *Teacher Education Quarterly, 28*, 109-114.

Monaghan, J. M., & Clement, J. (2000). Algorithms, visualization, and mental models: High school students' interactions with a relative motion simulation. *Journal of Science Education and Technology, 9*, 311-325.

National Council of Teachers of Mathematics. (1991). *Professional standards for teaching mathematics*. Reston, VA: NCTM.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Council. (2000). *How people learn: Brain, mind, experience, and school*. Washington, D.C.: The National Academies Press.

National Science Teachers Association. (2009). Science teacher induction programs: NSTA position statements. Retrieved October 2, 2009, from http://www.nsta.org/about/positions/induction.aspx

National Staff Development Council. (2001). *Standards for staff development*. Retrieved 3/31/11. from http://nsdc.org/standards/index.cfm.

Park Rogers, M., Abell, S. K., Lannin, J., Wang, C. Y., Musikul, K., Barker, D., et al. (2007). Effective professional development in science and mathematics education: Teachers' and facilitators' views. *International Journal of Science and Mathematics Education, 5*, 507-532.

Patton, M. Q. (2002). *Qualitative research and evaluation methods* (3 ed.). Thousand Oaks, CA: Sage Publications, Inc.

Piaget, J. (1951). *The psychology of intelligence*. London: Routledge and Kegan Paul.

Piaget, J. (1952). *The origins of intelligence in children*. New York: International University Press.

Pirie, S. E. B. (1996). *Classroom video-recording: When, why, and how does it offer a valuable data source for qualitative research*. Paper presented at the annual meeting of the North American Chapter of the International Group for the Psychology of Mathematics Education.

Podolefsky, N. S., & Finkelstein, N. D. (2006). Use of analogy in learning physics: The role of representations. *Physical Review Special Topics - Physics Education Research, 2*, 020101.

Putnam, R., & Borko, H. (1997). Teacher learning: implications of new views of cognition. In B. J. Biddle, T. L. Good & I. F. Goodson (Eds.), *The international handbook of teachers and teaching* (pp. 1223-1296). Dordrecht, The Netherlands: Kluwer.

Richardson, J. T. E. (1999). The concepts and methods of phenomenographic research. *Review of Educational Research, 69*, 53-82.

Roehrig, G. H., & Luft, J. A. (2006). Does one size fit all? The induction experience of beginning science teachers from different teacher-preparation programs. *Journal of Research in Science Teaching, 43*, 963-985.

Rolheiser, C., & Hundey, I. (1995). Building norms for professional growth in beginning teachers: A learning consortium initiative. *School Effectiveness and School Improvement, 6*, 205-221.

Russell, T., & Martin, A. K. (2007). Learning to teach science. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of Research on Science Education* (pp. 1151-1178). Mahwah, NJ: Lawrence Erlbaum Associates.

Schempp, P. G. (1995). Learning on the job: An analysis of the acquisition of a teacher's knowledge. *Journal of Research and Development in Education, 28*, 237-244.

Schmitt, R. (1967). Phenomenology. In P. Edwards (Ed.), *The encyclopedia of philosophy* (Vol. 6, pp. 135-150). New York: Macmillan.

Sheppard, K., & Robbins, D. (2005). Chemistry, the central science? The history of the high school science sequence. *Journal of Chemical Education, 82*, 561-566.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*, 4-14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*, 1-22.

Skinner, B. F. (1938). *The behavior of organisms*. New York: Appleton-Century-Crofts.

Smith, T. M., & Ingersoll, R. (2004). What are the effects of induction and mentoring on beginning teacher turnover? *American Educational Research Journal, 41*, 681-714.

Stigler, J. W., & Hiebert, J. (1999). *Teaching gap*. New York: Free Press.

Svensson, L. (1997). Theoretical foundations of phenomenography. *Higher Education Research and Development, 16*, 159-171.

Torres, S. (2006). A TIME for physics first: Academy for teachers - inquiry and modeling experiences for physics first. University of Missouri: Missouri Department of Elementary and Secondary Education.

Uljens, M. (1996). The essence and existence of phenomenography. In G. Dall'Alba & B. Hasselgren (Eds.), *Reflections on phenomenography: Toward a methodology?* (pp. 105-130). Göteborg: Acta Universitatis Gothoburgensis.

van Driel, J. (1999). Teachers' knowledge of models and modelling in science *International Journal of Science Education, 21*, 1141-1153.

van Driel, J., De Jong, O., & Verloop, N. (2002). The development of preservice chemistry teachers' pedagogical content knowledge. *Science Education, 86*, 572-590.

van Driel, J., Verloop, N., & de Vos, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching, 35*, 673-695.

Van Heuvelen, A., & Zou, X. (2001). Multiple representations of work-energy processes. *American Journal of Physics, 69*, 184-194.

van Maanen, J. (1996). Ethnography. In A. Kuper & J. Kuper (Eds.), *The social sciences encyclopedia* (2nd ed., pp. 263-265). London: Routledge.

van Rossum, E. J., Deijkers, R., & Hamer, R. (1985). Students' learning conceptions and their interpretation of significant educational concepts. *Higher Education, 14*, 617-641.

Veal, W. R., & Kubasko, D. S. (2003). Biology and geology teachers' domain-specific pedagogical content knowledge of evolution. *Journal of Curriculum and Supervision, 18*, 334-352.

Veal, W. R., Tippins, D. J., & Bell, J. (1998). *The evolution of pedagogical content knowledge in prospective secondary physics teachers*. Paper presented at the the annual meeting of the National Association for Research in Science Teaching.

von Glasersfeld, E. (1995). A constructivist approach to teaching. In L. Steffe & J. Gale (Eds.), *Constructivism in education* (pp. 3-16). New Jersey: Lawrence Erlbaum Associates, Inc.

Vygotsky, L. (1978). *Mind in society: The development of higher psychological processes*. MA: Harvard University Press.

Wang, C. Y., & Volkmann, M. (2007, April). *Dynamic model of pedagogical content knowledge*. Paper presented at the the annual meeting of the National Association for Research in Science Teaching, New Orleans, LA.

Wang, J., & Odell, S. J. (2002). Mentored learning to teach according to standards-based reform: A critical review. *Review of Educational Research, 72*, 481-546.

Watson, J. B. (1913). Psychology as the behaviorist views it. *Psychological Review, 20*, 158-177.

Wertsch, J. V. (1997). *Vygotsky and the social formation of mind*. Cambridge: Harvard University Press.

Wilson, S. M., & Lowenberg, D. (1991). *Changing visions and changing practices: Patchworks in learning to teach matematics for understanding* (Research Report

91-2). East Lansing, MI: The National Center for Research on Teacher Educationo. Document Number)

Zeichner, K. M. (1993). Traditions of practice in U.S. preservice teacher education programs. *Teaching and Teacher Education, 9*, 1-13.

Zubrowski, B., Troen, V., & Pasquale, M. (2007). *Making science mentors: A 10-session guide for middle grades*. Arlington: NSTA Press.

APPENDIX A: INTERVIEW PROTOCOL

Veteran Physics Teacher Observation Cycle Protocol

Submitted by the teacher via email to the researcher 48 hours prior.
Written plan (*Purpose: to provide a written guide for the observer*)

I would like to observe your teaching for the duration of this unit (2 weeks). Please send me your plan for this unit and answer the following:

- What science do you want the students to learn?
- Describe what will happen during the beginning, middle, and end of each class. What will you do? What will the students do?
- How will you know the students learned what you wanted them to learn?
- Describe what will be needed for this unit (e.g., resources, materials, equipment, etc.)
- Include copies of any handouts, overhead transparencies, assessments, etc. that you plan to use.

Prior to first observation:
Researcher role: My role is to assume a stance of empathic neutrality. That is, I will empathize with the participant and care about him/her. However, my role is to UNDERSTAND, not to Evaluate or Teach. I will keep these ideas in mind during my visit.

Pre-Observation Interview

Part I. *Purpose: to clarify the plans and uncover the teacher's PCK and knowledge of representations*

Opening Questions

1. Update me about what is going to occur over the next 2 weeks I am observing.
   a. What will we see in week 1? In week 2?
   b. What will you be doing?
   c. What will the students be doing?
   d. What are your purposes and goals for these 2 weeks?
   e. How did you decide on these purposes and goals?
   f. Why are these purposes and goals important to you?
   g. Fast forward 2 weeks. Imagine that you've successfully taught this unit. What would success look like? How will you know you've been successful?

Subject Matter Knowledge (SMK/CKT)
Say to the participant: One area that I am interested in is what I call content knowledge. In your case, I mean your own understandings of the science that you will be teaching.

2. What are your previous experiences with (this topic)?

    a. How well do you think you know (this topic)?
    b. Where did you learn about (this topic)?
    c. Have you taught (this topic) previously?

3. What do you think is important for students to know about (this topic)?
    a. Why do you think that is important?
    b. Could you walk me through your explanation of this concept?
    c. Tell me about where and how you learned these things.
    d. What else do you know about (this topic) that students might not need to know?

4. How do the science ideas in (this topic) relate to other science ideas?

5. What science content did you learn while preparing the lessons for this unit?

Knowledge of Learners

Say to the participant: Another part of what a teacher knows has to do with how students think about science. The next questions are designed to probe what you know about how students might think about (this topic).

5. Tell me about the students in this class, in terms of science.
    a. Tell me more about your students' attitudes about science.
    b. Tell me about your students' science abilities.
    c. How do you think this particular group of students learn science best? Why do you think that?
    d. How do you help the best students and how do you help the worst students without risk of alienation of either group?
    e. How have your experiences with these students influenced the way you teach?

6. What do you think students will already know about this topic?
    a. Why do you think that they may know that?
    b. Where do you think they may have learned this?

7. Do you expect students to have difficulty with anything that you have planned?
    a. What part of this will be the most difficult for them?
    b. How did you find out this was hard for them?
    c. Why do you think they will have difficulty with that?

    [Probe for SOURCES of Knowledge of Learners]

Knowledge of Instructional Strategies

Say to the participant: I want to know more about how you organized the instruction during this unit. The next questions will help me better understand your decisions about what and how to teach (this topic).

8. Talk to me about how you plan to help students learn the important science ideas you talked about earlier *(Probe for specifics based on the plan; use prompts in #9 to help you probe about parts to the plan).*

[*Note: the questions in #9 can be asked about any different stages of the plan. I am interested in how the teacher organized the flow of the class and why]*

9. From your plan, it appears that you chose to start the class (continue class; end the class) with __________________ (i.e., warm-up, lecture, experiment, investigation). Talk to me about making that decision.
    a. Why did you choose to start this way?
    b. Where did you learn about this way to start (continue; end) a class?
    c. Did you consider starting (continuing; ending) the class in a different way? Why/why not?
    d. What other plans did you consider?
    e. What other factors influenced your planning decisions?

10. I noticed that you used a picture (graph, equation, analogy…) in your plan. Tell me why you used that _____________ at that point in your plan.
    a. How do you think this (picture, graph, equation, analogy) helps students learn about (this topic)?
    b. Did you consider representing that idea another way?
    c. Where did this (picture, graph, equation, analogy) come from?
    d. Tell me about the sequence of representations you used in class today. Would it make a difference if you used a different sequence?

Knowledge of Curriculum

Say to the participant: These next questions are designed for us to know something about where your ideas for these two days came from.

11. Where did you get your ideas for teaching (this topic)? *Probe for sources.*
    a. Tell me about the materials (lecture notes, handout, transparencies) you prepared. Where did the materials (lecture notes, activities, worksheets, etc.) come from? *Probe for sources of activities as necessary.*
    b. What modifications did you make to existing materials?
    c. How do you think these materials will help or hinder achieving the purpose of your plans?

12. I have some questions for you related to how these plans relate to other topics that you might teach.
    a. How does that science fit into the bigger picture of what students learn in this class?
    b. How does (this topic) fit into the "big picture" of what students learn about science in high school?

Knowledge of Assessment

Say to the participant: The last area I want to ask you about is how you will know what students learn from these two weeks of class.

13. During the 2 weeks of instruction, what do you plan to assess? Why do you think it is important to assess this?

14. How do you plan to assess these (things)?
    a. Describe how you will find out if students learned what you intended? Are there other ways that you might know what your students learn in class on these two weeks?
    b. How will you find out what your students learned about (a specific idea within) the energy unit?
    c. Where did you learn about those strategies for finding out about what students learned?
15. What will you do with the information you gain from the assessment?
16. What challenges do you foresee as you assess students?

Is there anything else about your plans that you want me to know?

Part II. *Purpose: to capture the teacher's work history and PD history throughout his or her career*

Opening Statement

Say to the participant: The purpose of this next section of the interview is to help me understand your work history and professional development history over the course of your career. I would like to construct a timeline with you on this piece of paper highlighting your experiences.

1. When did you finish your undergraduate degree or get your teaching credentials?
2. Did you get a teaching job after getting your credentials?
3. Where was your first job? What did you teach? What was the school like? The students? How long were you at this job?
4. What type of professional support did you have at your first job? Are there any supports that really stand out to you as being significant?
5. If you moved from that first school to another school, when did that happen? What did you teach? What was the school like? The students? How long were you at this job?
6. What type of professional support did you have at this job? Are there any supports that really stand out to you as being significant?

[*keep asking this series of questions for all jobs that the participant has had]*

7. Can you tell me about any significant professional development experiences that you have had over your career? These might include workshops, conferences, PLTs, seminars, book clubs, course work, etc. Anything that you can think of that has supported you as a teacher over your career.

[*for each PD experience, ask the following questions]*

8. When did this PD occur in your career? Was it something you chose to participate in or were you required to participate in it? How long did it last? Where was it? What was the format like? Was it specific to a certain topic?

Thank you again for participating in this interview.

During the Observation
The observer(s) will have selected interesting instances regarding the teacher's use of representations to discuss. What constitutes an interesting instance?

Knowledge of Learners
Student making a profound comment about a representation and the teacher does or doesn't recognize it or misinterprets what the student says or does.
Student makes a comment that demonstrates confusion about a representation, and the teacher does or doesn't recognize or misinterprets why the student is confused?
Teacher explicitly recognizes potential student difficulties regarding a particular representation

Knowledge of Instructional Strategies
The teacher makes an instructional decision regarding the use of a representation that alters the flow of the classroom by asking a question or directing students to perform a particular task.
The teacher uses a representation to clarify an idea.

Knowledge of Curriculum
A particular representation is chosen that may or may not elicit the student thinking that was intended.
The teacher modifies a representation "on the fly" based on what occurs in the classroom.
Teacher refers to science representations in other parts of the course/curriculum (vertical or horizontal curriculum alignment).

Knowledge of Assessment
Teacher uses a representation to ascertain student prior knowledge.
The teacher recognizes that the students are having difficulty with a particular representation.
The teacher uses a low-level representation as assessment such as providing an bar graph that requires students to define rather than explain or synthesize.
The teacher acts on data collected from using representations during student assessment.

SMK
Teacher demonstrates particularly strong SMK.

Teacher demonstrates inaccurate SMK.

After each observation:
Stimulated recall interview (*purpose: to have the teacher immediately reflect on the instruction as a window into PCK and representations and to connect to pre-interview)*.

Stimulated Recall Interview

1. How do you think the lesson went? In what ways was the lesson I observed different than other periods you taught it? Different from your plans?
2. I have selected some parts of the instruction that I found particularly interesting. I want to watch them together and ask you some questions about them.

   Let's watch this part (interviewer asks questions starting in one of the following categories based on the reason for selecting the specific interesting instance).
   a. What were you thinking when this was occurring? Tell me more about what was happening when you __________.
   b. **[K of Instructional Strategies/Representations]** Tell me about that representation (graph/chart/sketch/)? Why did you decide to use that? How did this representation help you achieve your overall goals? ***Be sure to probe for experiences and changes in knowledge!!***
      i. How could you use this representation in a different way? Where did you learn to use it that way? Have you always used that? When did you first start using it in that way? Why did you start using it that way? What experiences informed the way you use it now?
      ii. I remember from one of our earlier interviews and from your timeline that you had a professional development experience (workshop, seminar, class, etc) on this topic. Did that experience influence the way you decided to use representations today? How? What was it about the PD experience that prompted you to change this way?
      iii. How did this representation help you achieve your overall goals? How does the way you used it reflect your understanding of how students learn? Do you remember any experiences that caused you to think about using representations in this way? Tell me about that experience? What made it so powerful?
      iv. [*NOTE: questions about instructional strategies should probe all of the different ways that the participant might know to teach a particular topic. For this PCK component, I am interested in "mining" the participants' knowledge about all kinds of different representations as instructional strategies. I will ask this series of questions many times during the interview*.]
   c. **[K of Learners]** ***Be sure to probe for experiences and changes in knowledge!!*** What do you think the student was thinking? Why do you think the student was having difficulty at that point? What knowledge about students did you use to make instructional decisions about representations? What misconceptions do students typically have when using this representation? What do student

difficulties with this representation typically look like? How do you know? In what ways did students influence your teaching decisions regarding representations today? How will you help your students construct this representation? How will you make it relevant to their everyday life? How will they see its usefulness? How will the students use the representation? How might you modify your instruction if a student used a representation in this certain way?

d. **[K of Curriculum]** ***Be sure to probe for experiences and changes in knowledge!!*** Did the representations achieve the purpose you intended? Why do you think that? How did your curriculum materials support or hinder you in implementing your plan in regards to using representations? In what other topics/units can this representation be used? Why did you decide to use it for this topic? Is there a different representation that you could have used?

e. **[K of Assessment]** ***Be sure to probe for experiences and changes in knowledge!!*** What do you think students got out of using representations today? How do you know? Tell me about how you found out about student learning in regards to representations. Why did you decide to do that? Where did that idea come from? How do you think it worked? What does student understanding look like as demonstrated by their use of this representation? How do you know? How might you use this representation to formatively assess your students? How could you use it to summatively assess your students? What are the differences in how the representation would be used in each case?

f. **[SMK]** ***Be sure to probe for experiences and changes in knowledge!!*** What science content regarding representations did you learn while teaching this lesson? What are the strengths of this representation? What are the limitations of this representation? What are the essential features of the representation and why are they important? What essential questions can be answered with this representation? What understandings does it help construct? Are there problems that cannot be solved with this representation?

g. **[SMK]** Given the opportunity to sit down with a colleague you trust, what questions would you ask about representations for this topic?
h. [**SMK**] What were the critical science ideas regarding representations in today's lesson?

3. Was there a time during the instruction when you changed your plan for using representations? Tell me about that.
4. Based on what happened today, what do you plan to do the next couple of days? Will you change anything from your original plans?

[*Note: Ask these questions on the last interview*]
5. [**Orientations**]. ***Be sure to probe for experiences and changes in knowledge!!*** Imagine your best day of teaching science using representations.
a. Describe what makes it a "best day" for you.

b. How do these lessons that you've taught compare to your "best day" description.

6. [**Orientations**]. Now consider a typical day of teaching using representations for you.
   a. What is the teacher's role in a typical lesson in terms of using representations?
   b. What is the students' role in a typical lesson in terms of using representations?
   c. How do you prefer to use representations when you teach?
   d. How does this compare to other teachers?
   e. How does this compare to what you've learned in your PD experiences?
   f. In what ways have your ideas about teaching changed since you began teaching? Probe for sources of these changes.
   g. Now think of yourself as a science learner, how do you best learn science concepts?

APPENDIX B: INFORMED CONSENT

UNIVERSITY OF MISSOURI
EXPERIENCED TEACHER INFORMED CONSENT

Development of Veteran Physics Teachers' Knowledge of Using Representations

The purpose of this research study is to investigate the knowledge of experienced science teachers. This research study will be conducted in the fall semester of 2010.

INFORMATION

You must be at least 18 years of age to be eligible to participate in the study. Your participation in this study is voluntary; you may choose not to participate and there will be no penalty or consequence to you. If you decide to participate, you may withdraw from the study at any time without penalty. Only members of our research team will know the identity of individuals who choose to participate in the study.

PARTICIPATION

If you decide to participate, you will agree to:

1) Participate in a pre-observation interview in which you will describe your lesson plans and prior professional development experiences a few days prior to teaching (approximately 90 min)
2) Submit lesson plans detailing your plans for teaching the energy unit
2) Open your classroom for observation for two weeks (including video recording of your teaching)
3) Participate in semi-structured interviews about your classroom instruction twice a week for two weeks at the end of the school day (approximately 90 min per interview).

BENEFITS

Your participation in this research study will add to our understanding of teacher knowledge. The information gained in this study may be useful to designers of teacher education and professional development programs and guide state and national policymakers regarding the guidelines these programs. The information gained in this study may be published and may also be useful to science teacher educators at other universities and colleges.

You will be compensated with $400 for your participation in this study. These activities will require approximately 20 hours of your time (1.5 hours for each of 5 interviews; 2.5 hours developing lesson plans; 10 hours opening up classroom for observations). Should you choose to withdraw from the study at any point, you will be compensated at the follow rates:

- Pre-observation interview = **$30**
- Submitting lesson plans = **$50**

- Opening classroom for observation = $20 per day X 10 days = **$200**
- Stimulated-recall interviews = $30 per interview X 4 interviews = **$120**
- TOTAL = **$400**

CONFIDENTIALITY

Your identity will be kept strictly confidential. Only members of the project team will know your identity. The data collected during the study will be stored in a secure area in Townsend Hall. In reporting the findings of this study, your name will be replaced with a pseudonym. You may choose to end your participation at any time during the study, and your data will be destroyed. The video recordings will not be used for analysis (only for the purposes of the interviews). They will not be viewed by anyone but you. Data will be stored for three (3) years beyond the completion of the study and at that time it will be destroyed.

RISKS

This project does not involve any risks greater than those encountered in everyday life.

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

CONSENT

Please read the consent statement below and place an "x" next to the statement that describes your desire to participate in this study at this time. Sign and date the form.

I have read the information presented above and have had an opportunity to ask questions and receive answers pertaining to this project.

________________ I hereby **agree** to participate in this research study. I am aware that my participation is voluntary and that I am free to withdraw participation at any time without any penalties to myself.

________________ I **do not agree** to participate in this research study.

Signed: ____ Date: ________________

Printed Name: ____

Thank you. If you have questions at any time, please call Andrew West, Lead Project Investigator, at the University of Missouri at (816) 536-1139.

VITA

Andrew West grew up in the rural mountain town of Westcliffe in south-central Colorado. He graduated high school in 1999. In 2003, Andrew earned a Bachelor's degree in biology from Montana State University in Bozeman, Montana. After graduation, Andrew accepted a position as a high school science teacher at Custer County High School in his hometown of Westcliffe, Colorado. During his three years at Custer County High School, Andrew taught a variety of science subjects, including physics, chemistry, physical science, biology, and ecology. During this time, Andrew completed an alternative certification program to secure his Colorado State Professional Teacher's License. Andrew taught at the high school for three years.

In 2006, Andrew left Colorado and moved with his wife to Columbia, Missouri, to pursue a Master's degree in science education from the University of Missouri (MU). During this time, Andrew worked as a coach/mentor for the MU Physics First professional development project and as a supervisor for secondary science education student teachers. Andrew completed his Master's degree in 2008 and decided to continue working towards his Ph.D. at MU. In 2009, Andrew transitioned out of his mentoring and supervision roles and joined the MU Re-SMAR^{2}T project team as a graduate research assistant during which he explored teacher knowledge in alternative certification programs. Andrew completed his doctoral degree in the spring of 2011 with Dr. Mark Volkmann as his advisor. Andrew's future plans include working as a post-doctoral scholar in the MU Science Education Center, where he will focus on teaching, mentoring, and research.