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ABSTRACT

The purpose of this study was to describe the evolution of pedagogical content knowledge (PCK) in prospective secondary physics teachers. Craft knowledge was used as one epistemological perspective. The researcher used two cases, two prospective physics teachers, and followed their development through the science curriculum class and student teaching field experience of their teacher preparation program. Content-specific, situational vignettes were created as a tool to monitor the participants' development of PCK. Data were collected through several methods and were analyzed using qualitative content analyses. The results of this study support three major findings about the development of PCK in prospective secondary physics teachers. First, the prospective physics teachers believed that experience in the classroom was an integral part of their development. Second, prospective teachers became student centered in their teaching approach and began to reflect and philosophize about their beliefs of science teaching and learning. Third, the development of PCK was determined to be complex and non-linear. In particular, content knowledge, followed by knowledge of students, were determined to be the most important knowledges in the development of PCK. Knowledge of content and students formed a base from which prospective teachers could develop domain-specific PCK. (Contains 57 references.) (Author/ASK)

The Evolution of Pedagogical Content Knowledge in Prospective Secondary Physics Teachers.

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The purpose of this study was to describe the evolution of pedagogical content knowledge (PCK) in prospective secondary physics teachers. Craft knowledge was used as one epistemological perspective. The researcher used two cases, two prospective physics teachers, and followed their development through the science curriculum class and student teaching field experience of their teacher preparation program. Content-specific, situational vignettes were created as a tool to monitor the participants' development of PCK. Data were collected through several methods, and analyzed using qualitative content analysis. The results of this study support three major findings about the development of PCK in prospective secondary physics teachers. First, the prospective physics teachers believed that experience in the classroom was an integral part of their development. Second, prospective teachers became student centered in their teaching approach, and began to reflect and philosophize about their beliefs of science teaching and learning. Third, the development of PCK was determined to be complex and non-linear. In particular, content knowledge, followed by knowledge of students, were determined to be the most important knowledges in the development of PCK. Knowledge of content and students formed a base from which prospective teachers could develop domain-specific PCK.

Reform movements in the past decade have focused on the establishment of a knowledge base for teacher education (American Association for the Advancement of Science, 1992; National Research Council, 1996). As part of the professional development standards, the National Research Council published a set of standards for science education reform at the national level. The *National Science Education Standards* (1996) initiated a discussion on a knowledge base that could be used to guide science curriculum development and teacher practice. Pedagogical content knowledge (PCK) was introduced as a professional development standard and knowledge base that could be used for science teacher education reform.

Purpose of the Study

The term *knowledge base* has become a popular term most recently used in the rhetoric of teacher professionalism and teacher education. Knowledge bases have recently been incorporated into accreditation standards for teacher certification programs (National Council for Accreditation of Teacher Education [NCATE], 1987). The assumption was made that a knowledge base or knowledge bases existed, and that every faculty ought to justify how its knowledge base(s) formed the foundation of its teacher education program. The NCATE standards recognized two types of knowledge bases: "the traditional forms of scholarly inquiry as well as theory development related to professional practice" (NCATE, 1987, p. 37). The traditional form was associated with applied science, and theory development was more closely associated with teachers' knowledge or practical knowledge.

With documents of the past decade, such as *A Nation at Risk: The Imperative for Educational Reform* (1983), *Tomorrow's Teachers: A Report of the Holmes Group* (1986), *A Nation Prepared: Teachers for the Twenty-first Century* (1986), and *Science for All Americans* (1990), education has been under more pressure than ever to reform. One aspect of this reform, as mentioned in these documents, was the need for a professional knowledge base for teacher education programs. Fenstermacher (1994) stated:

> In the United States, many members of the policy-making community are embracing a view of teacher knowledge and skill that represents a limited epistemological perspective on what teachers should know and be able to do. It is grounded in a conception of the social and behavioral sciences that are themselves constructed isomorphically to the physical sciences...This knowledge base, in turn, gives rise to such policy initiatives as national certification for teachers, accountability and performance assessment in teaching, research based designs for the accreditation of teacher education, and some (but not all) of the current initiatives in the development of subject field, grade-level, and state-level standards for student learning (p. 4).

Fenstermacher (1994), like Carter (1990), believed that the knowledge base, embraced by members of the policy-making community, for teacher education programs was problematic. Fenstermacher maintained a belief that the effect of the current knowledge base had influenced too many parts of teacher certification. According to Fenstermacher (1994), educational policy was not to be grounded in weak or esoteric concepts about the nature of knowledge; a solid and understandable knowledge base that described the essential elements of teaching was needed. By striving to adopt high standards, researchers have recently sought knowledge bases which reflected both teachers' and researchers' perspectives, and had epistemic qualities.

The need for a coherent knowledge base for science teacher education has been warranted. Cochran, King, and DeRuiter (1991) stated that teachers developed their pedagogical skills independently from their content knowledge. Pedagogical content knowledge has been suggested as that unifying principle or tenet for teacher education (Smith, 1997). What has remained unclear with respect to the standard documents and teacher education is the process by which a prospective or novice science teacher develops the ability to transform knowledge of science content into a teachable form.

Review of Relevant Literature

Knowledge bases are conceptions which are epistemologically "thrown around" by researchers (Kliebard, 1993; McEwan & Bull, 1991), accrediting agencies (Johnson & Erion, 1991), and teacher education programs (Johnston, 1992). The teacher education literature reflects a myriad of different types of "conceptions of knowledge " (i.e., formal, practical, location-specific, expert, contextualized, craft, teacher, personal practical, propositional, local, pedagogical, curricular, content, subject specific, research, theoretical, pedagogical content, etc.). All of these knowledge bases represent ways of viewing teaching and the knowledge of teaching, and only differ in their context of use.

Some researchers have called for the establishment of a knowledge base for teacher education (Anderson & Mitchener, 1994; Darling-Hammond & Goodwin, 1993; Shulman, 1987; Yeany, 1991). Kliebard (1993) described the historical evolution of the knowledge base for the "scientific training" of teachers, and based his description on Rice's (1891) article emphasizing the importance of scientific training of teachers. Kleibard (1993) wrote that education was "characterized by schools based on sound scientific principles rather than what he [Rice] liked to call mechanical practices" (p. 296). The public indifference to education at the turn of the century set the groundwork upon which a foundation for teaching would be built. The foundation for teaching became known as a knowledge base. Taylorism was one of the first knowledge bases to be used in education. Taylorism was a principle in which the "desired learning goal in the most efficient, least time consuming, minimally wasteful manner" was achieved (Kleibard, 1993, p. 297). Because education under Taylorism took on a business and scientific like structure, some believed a new knowledge base had to be developed. Zeichner (1983) stated that there have been at least four paradigms that have dominated teacher education since Taylorism: behaviorism, personalistic, traditional-craft, and inquiry-oriented. Some remnants and ideas of these knowledge bases exist in curricula and instructional practices today.

In recent years there has been more discussion about the essential components of certain knowledge bases, with a focus on the practice of teaching. Wilson, Shulman and Richert (1987) associated the term "knowledge base" with applied science. "It refers to the set of rules, definitions, and strategies needed by a computer to perform as an expert would in a given task environment. That set of rules is usually rather specific to a particular domain or task" (p. 107). This domain or task helped define a knowledge base for science or for a specific domain of science, such as physics. Wilson, Shulman and Richert (1987) defined the knowledge base for teaching as "the body of understanding, knowledge, skills, and dispositions that a teacher needs to perform effectively in a given teaching situation" (p. 107). Other researchers have developed their own definitions or taxonomies for what components should be present in the practice of teaching (Shulman, 1987; Tamir, 1988). These taxonomies incorporate the ideas of the practice of teaching into knowledge bases that reflect the ideas of an applied science (Grossman, 1987; Hoz, Tomer, & Tamir, 1990).

Carter (1990) believed that teacher education programs were using the wrong knowledge base for understanding the practice of teaching. Instead of using the knowledge held and used by teachers and student teachers, teacher education programs have used the knowledge of what university professors believed to be correct. According to Carter, the knowledge of the university professor was most likely not practical or considered by teachers, themselves, to be the "correct knowledge." Carter's argument raised what researchers determined was a problem in education research. Whose research and whose knowledge were researchers studying and using? Veal and Tippins (1996) argued that the knowledge of teaching was held by individual teachers within classrooms, and that research (action research) should focus on teachers' ways of expressing their knowledge from a personal perspective, rather than from a researcher's perspective. Fenstermacher (1994) also believed that there was a knowledge held by teachers that was both practical and needed.

> Of particular interest is the growing research literature on the knowledge that teachers generate as a result of their experience as teachers, in contrast to the knowledge of teaching that is generated by those who specialize in research on teaching (Fenstermacher, 1994, p. 3).

This alternative view of teacher knowledge has allowed for researchers and teachers to view the knowledge base of teaching in a different manner, practically oriented rather than as an applied science.

Craft knowledge was used as one epistemological perspective in this study. Shulman (1987) stated that the "wisdom of practice" was a major source for the teaching knowledge base of PCK. Leinhardt (1990) stated that "expert teachers possess a practical knowledge of their craft, which is sometimes called the wisdom of practice" (p. 18). Craft knowledge has not been used before in science education to view the practice of science teaching. The practical nature of craft knowledge blends well with a study focusing on PCK, because the two epistemologies are inherently related by the emic, reflective, and practical characteristics of each one (Fenstermacher, 1994; Grimmett & MacKinnon, 1992).

Craft knowledge has been closely linked to pedagogical content knowledge due to the practical aspect inherent in each knowledge base. Leinhardt (1990) stated that pedagogical content knowledge was one aspect of craft knowledge. The problem in her assessment device of what teachers should know in order to teach, centered on how one could tell whether a teacher had developed pedagogical content knowledge or craft knowledge. On the other hand, Johnston (1992) suggested that pedagogical content knowledge might be "viewed as a sub-set of practical knowledge" (p. 124). Similarly, Carter (1990) viewed pedagogical content knowledge as a more distinct domain related to practical knowledge. According to Carter (1990), the difference was that pedagogical content knowledge was more greatly grounded in a discipline than the broader "collective wisdom of the profession" associated with practical knowledge. Gudmundsdottir (1991) wrote, "As a body of knowledge developed mostly through practice, pedagogical content knowledge retains some of the elements that characterize the knowledge of those who work with people in the practical domain" (p. 7).

Grimmett and MacKinnon (1992) stated that pedagogical content knowledge was one component of craft knowledge, the other being pedagogical learner knowledge in accordance with how Johnston (1992) and Carter (1990) viewed the term. Grimmett and MacKinnon (1992) argued that pedagogical content knowledge was epistemologically different from the other six categories that Shulman (1987) used to describe the knowledge base of teaching. The other six categories included principles of teaching that could be learned in methods class and later practiced and applied in the classroom. They asserted that pedagogical content knowledge concerned itself with "teachers' representations of subject matter content in terms of how it might be effectively taught" (p. 387). Grimmett and MacKinnon (1992) also asserted that pedagogical content knowledge was "derived from a considered response to experience in the practice setting...it is formed over time in the minds of teachers through reflection" (p. 387). These attributes of pedagogical content knowledge and craft knowledge mirror those of practical knowledge found in national standards and documents.

Methodology

The inquiry process that guided this study was qualitative in nature. This research was a case study characterized by theory and action (Merriam, 1985; Stake, 1995, 1996; Yin, 1993). The case study was conducted with 2 prospective secondary physics teachers in two settings: the secondary science curriculum class, and the subsequent student teaching field experience. These cases represented the unit of analysis for the study. The focus of the inquiry was on the cognitive development of PCK. The questions the researcher brought to the forefront in this study (both implicit and explicit) were informed by his experiences in teaching science in a secondary physics context and by knowledge of previous research on science teachers' learning and teaching.

Since one of the purposes of this study was to monitor the evolution of PCK in secondary science prospective teachers, the researcher assumed that a change to some degree would occur within each individual as she constructed new meanings about science teaching.

Change was monitored using a variation of the microgenetic method in which participants responded four times to the same content specific vignette during each of the two phases of the study. The first response phase occurred during the science curriculum class with the second response phase that took place during the student teaching field experience.

Context of the Study

This study took place in a secondary science curriculum/methods class taught at a large university in the Southeast and in secondary science classrooms serving as placement sites for the prospective teachers during their student teaching field experience. The researcher acted as a participant observer during the secondary curriculum class and the students' field experiences. Both of the participants, Maggie and Tami, held baccalaureate degrees in a science content area.

Data Sources

Multiple data sources were used during the research process. Structured and semi-structured interviews were conducted with the prospective teachers, classroom teachers, and the instructor of the secondary science curriculum/methods class. Documents pertaining to the secondary science curriculum/methods class (philosophy statement, handouts, and course syllabus) were collected and used in generating questions asked during interviews with the professor. Field notes were taken during the methods class and the student teaching field experience. Participants were asked to keep reflective journals about their experiences and thoughts during the curriculum/methods class and field experience. Participants were also asked to share and discuss classroom projects and assignments.

A variation of the microgenetic method was used in this inquiry to study the evolution and developmental change in prospective secondary science teachers. The microgenetic method describes a procedure whereby the participants receive frequent encounters with the same task over a period of time (Siegler and Crowley, 1991). The microgenetic method was ideal for studying the evolution of PCK and its characteristics in prospective secondary science teachers, because participants were able to respond to a task (vignettes) over the course of two stages of teacher certification.

The content specific situational vignettes created for this study promoted thoughtful reflection about potentially problematic incidents that could easily happen in any teacher's classroom (Stivers, 1991). The administration and use of the vignettes as a heuristic tool in this study were purposeful. The vignettes constituted a modified intervention strategy designed to facilitate inquiry. The two theoretical frameworks of this study, craft knowledge and PCK, were consistent with the use of vignettes because the vignettes reflected teachers' practice within a specific topic.

Vignettes

Most of the vignettes found in the literature (Greenwood & Parkway, 1989; Kowalski, Weaver, & Henson, 1990; Shulman & Colbert, 1988; Silverman, Welty, & Lyon, 1992; and Walen & Williams, 1995) focus around pedagogical issues, not content. The vignettes developed for this study involve classroom management, student learning, teaching styles and methods, science content, multicultural issues, and inaccuracies in science content. Several researchers have suggested processes for creating vignettes (Lieberman, 1987; Miles, 1987; Stivers, 1987; and Walen & Williams, 1995). The vignettes used for this study contain the following components; an introduction of the setting, a description of the participants, an explanation of the problem, a description of the interacting dimensions found in the classroom, the dialogue between participants, and a possible major event worthy of attention by the teacher.

The researcher administered the first vignette to each prospective teacher four times during the secondary science curriculum class: the second week of class, three weeks later, during the practicum experience in the eighth and ninth week of the quarter, and during the last week of class. The researcher administered the second vignette to each participant four times during the student teaching field experience. Due to the scheduling nature of the student teaching field experience, the researcher administered the vignettes approximately every two to three weeks. Depending upon how each participant responded to the vignette, the researcher asked either probing questions related to her initial responses, or asked a set of pre-determined questions. The questions were open-ended in the style of Spradley's (1979) "grand tour" questions, and did not lead the student to explicate correct answers.

Overview of the Physics Vignettes

The vignette Maggie and Tami responded to in the first phase of the study was entitled *Linear Motion* (Vignette A). In this vignette, the teacher used a variety of teaching methods to introduce the concepts of speed, velocity, and acceleration. The teacher instructed using an open demonstration and discussion format. The teacher and students discussed, calculated, and defined linear motion concepts using a remote controlled car in the middle of the classroom. The PCK situations embedded within this vignette focused on 1) the incorrect teaching of some concepts of linear motion (linear motion can occur on the ground or in the air), and 2) a student who dropped the class, because his learning style did not fit well with the teacher's instructional methods (mini-lab was completed with non-motorized cars following a demonstration with a motorized car).

In the second phase of the study, Maggie and Tami responded to a different vignette entitled *Heating the Discussion with Thermodynamics* (Vignette B). In this vignette, the teacher used a variety of pedagogical methods to teach the concept of heat, temperature, and other concepts related to thermodynamics. He demonstrated concepts, lectured, lead a discussion, and had the students complete a mini-lab. The situations embedded within this vignette focused on 1) the use of a teaching method which was not conducive to all types of learners in the class (used an analogy of a waterfall to explain conservation of energy), and 2) the incorrect teaching of some concepts of thermodynamics (heat is the amount of energy it has). The vignettes could represent a real life physics classroom in the eleventh and twelfth grades.

Data Analysis

All text data (interview transcripts, documents, field notes, vignette responses, and journal entries) were analyzed by qualitative content analysis (QCA). This method was a general method of analysis, which was purely descriptive. Eight steps were used in the QCA. For example, emic categories were established based upon the units of meaning and their relationship to the research questions, and clusters of categories helped to diagram a scheme which represented findings relevant to the research questions (Strauss, 1987). The data were re-read and categorized into broad categories. Sub-categories were determined to organize the data further. Some of the emergent broad categories served as the foundation for questions in the participants' reflective and exit interviews. This was done as a type of member check of the analysis process.

Participants

Maggie is a single white female in her middle twenties with no children. She received her bachelor's degree in astrophysics from a small private women's college in the Southeast. After spending one year studying astrophysics in graduate school, Maggie decided to obtain certification to teach science at the secondary level. She had always wanted to share her passion of physics, especially astronomy, with others. Teaching, to Maggie, came naturally. Her experiences as a laboratory assistant in college and graduate school helped her to realize that she wanted to enter the teaching profession. Because of Maggie's teaching experience before entering the science teacher preparation program, she had a fairly well established philosophy about teaching. As Maggie progressed through the teacher preparation program, her initial ideas about science teaching changed slightly.

Maggie's student teaching placement was in a small rural high school containing grades seven through twelve. She taught eighth grade Earth science, junior chemistry, and senior physics. Her physics teaching was based upon the book Modern Physics by Holt, Rinehart, and Winston, 1984 edition. Her lesson plans, tests, and homework problems were based on the textbook. She did perform some demonstrations with the help of her cooperating teacher. Maggie believed that her method of instruction was flexible, even though it mainly consisted of lecture, example problems, demonstrations of some concepts, and homework problems. Maggie initially believed that teaching was teacher centered. She assumed that the teacher had to have control over the lesson and class. Maggie "flexed her muscles" early in the teacher preparation program, but during her student teaching field experience, she came to understand that the teacher was not the center of instruction.

Tami is a married white female in her mid thirties with three children. She received her Bachelor's degree in pharmacy. She has worked part time as a pharmacist for the past ten years. Tami has had some teaching experience working in her children's elementary classrooms. She has also substituted at a local high school. She decided to change careers and become a teacher, because she loved children and science, and enjoyed explaining science concepts to others.

Tami's student teaching placement was in a semi-rural high school with a diverse minority population that included Hispanics and blacks. She taught physics and physical science.

Her lesson plans for physics followed the chapters in the book Physics: Principles and Problems by Merrill. Tami's instructional format consisted primarily of lecture, supplemented with some activities, problems, and demonstrations (Lesson plans). She used the overhead projector as a lecture tool. Tami used traditional methods of assessment including problems, vocabulary quizzes, and laboratory write-ups. Tami used the metaphor of teacher as conductor, because she believed that she could coordinate students' learning. Tami believed that the musical instruments in an orchestra represented the students. She also believed that the conductor had to bring all of the different students together.

Results

Teaching and Learning Philosophies and Beliefs

Maggie believed that the best teaching style was one that involved the teacher in making content applicable to the lives of the students. "I want to be able to make it accessible to the real world" (Initial interview, 10/12/96). Maggie developed her opinion about an appropriate teaching style from her experience as a laboratory instructor in graduate school. As a teacher, Maggie wanted to "reach different students because they learn differently" (Initial interview, 10/12/97). Maggie believed that the best teaching style focused on the students. Maggie's philosophy of science teaching was partly synthesized from her observation of many different teachers modeling various methods of instruction. One way in which Maggie believed she would learn to teach science was to incorporate other teachers' methods into her classroom.

Tami based her teaching philosophy on how she learned science. "Well, recently I would have said lecture. Because that was when I was reflecting in 441 [Foundations on Science Education] I realized that when I pictured myself as teaching I pictured myself as lecturing"

(Initial interview, 10/12/96). In her initial interview, Tami used an analogy to expand on her image of teacher as lecturer.

> I guess it's what I've always had. And when I pictured myself as a teacher, I picture myself in front of the class lecturing...Like I wrote my rationale paper I see myself more as a conductor. You kind of orchestrate the students as they learn and I realize different students are on different waves. Some work better with really concrete objects, hands on, and some work better in abstract. It just depends on the kid, and you kind of coordinate their learning. But originally I see myself as a lecturer, which I thought was good. (Initial interview, 10/12/96)

For Tami, knowing the students and using hands-on instruction were two important components of teaching science. The only hands-on components Tami remembered as a student, herself, were experiences situated in the chemistry lab, where she usually kind of threw things together and they never quite turned out like they were supposed to" (Initial interview, 10/12/96). Tami came to realize during the process of becoming a teacher that the lecture method was not the only way to teach science.

Emergent Broad Categories in Physics Participants

The results of this study support three major findings about the development of PCK in prospective secondary physics teachers. First, the prospective physics teachers believed that experience in the classroom was an integral part of their development. Second, prospective teachers became student centered in their teaching approach and began to reflect and philosophize about their beliefs of science teaching and learning. Third, the development of PCK was determined to be complex and non-linear.

Experience is needed for PCK Development. Maggie's understanding of teaching expanded after she observed and taught a physics class during her practicum experience. Maggie came to realize the subtle, real-life aspects that contributed to the whole teaching and learning environment.

> Bureaucracy involved, discipline issues, attendance, homecoming, one girl got pulled out of class for a costume contest; paper work, balloons to be filled in, limited budget for photocopies. Ms. Fogle reduces all of her assignments. These are the real life aspects of teaching. We haven't seen all of it. We only see two periods. First period has to do announcements, attendance, and flag, and moment of silence, and still have to teach the same stuff in less time. Practical things about it, some I knew and some I didn't but not to the extent. (Practicum interview, 11/20/96)

By the end of the practicum experience, Maggie had developed a better understanding of different facets of teaching, and the multiple roles a teacher might assume in order to help students learn. Her new understanding of the classroom environment helped her analyze the linear motion vignette for situations other than content or pedagogy. Her recognition of the multifaceted dimension of the learning environment came to include the practical day-to-day routines and responsibilities of a teacher. Maggie's view of science teaching and learning had expanded to include the practical knowledge of the classroom teacher.

During Maggie's student teaching experience, she had the opportunity to further develop her ideas about using students' understanding of concepts to guide her instructional methods.

> As I get involved with my student teaching, I am developing much more definite ideas about what I do and do not want to do in my classroom. This is largely due to examples I've seen in my practicum and student teaching. I'm sure these things will change some as I gain experience and get to know what works best with a given group of students. (Journal entry, 1/10/97)

Maggie believed that her experiences teaching would provide her with more opportunities to improve her instructional methods. She also realized that her limited time in the classroom during student teaching was insufficient, and only the beginning of her development as a teacher. In Maggie's third response to Vignette B, she mentioned that a teacher was a life long learner, one who would build on prior experiences to develop professionally.

> As you teach the class more often you start to see patterns of what the students have a hard time with and what they seem to get OK, that they can recognize. OK, well last year, the students really had a hard time with this concept so maybe I should be prepared to,

> and I might have to teach that more and go into more detail and more explanation. But that's, a lot of it's just experience. (Vignette B3)

Maggie realized that practical experience was invaluable to her development as a teacher, particularly when it was under the guidance of excellent role models.

Tami's experiential knowledge about teaching science involved a developing understanding of the need to make concepts relevant to students' lives. As Tami learned to relate physics to students' lives, she was able to incorporate different aspects of the learning environment into her view of science teaching and learning. For example, in Tami's second response to Vignette A, she focused solely on Mrs. Johnson's explanation of the difference between speed and velocity.

> She just put velocity equals distance divided by time. And I think she's promoting them to understand, she put up the exact same formula for speed as she did for velocity. And she never did, I think she needed to make a greater distinction that direction was, she's promoted the misconception that velocity and speed are the same thing. (Vignette A2)

After spending time in a high school physics class observing and teaching, she was able to comment more specifically about the presentation of specific concepts in Vignette A, and their relationship to the students' lives.

> Yes, it has a vector quantity and yes, it has direction. But in real life we use speed and velocity fairly interchangeably. And reading through it this time, her explanation seemed to make more sense, and her questions seemed to make sense, and it seemed to have a more logical progression...Maybe it's just from being in the real world in the classroom and working with the kids. And if you get too hung up on the little points you can miss the whole picture. And she did say, Yes, it is direction, and she did bring in direction a couple of times. (Vignette A3)

By the end of the science curriculum class, Tami had begun to include the practical aspect of teaching into her overall perspective of science teaching and learning. She believed that a practical focus on the correct content would help students learn concepts. Thus, she began to emphasize a more practical application of content in her lessons.

Teachers Developed a Student Centered Approach. In the beginning of the study Maggie and Tami believed that the teacher should have control when teaching physics to students. Maggie and Tami did realize that students influence teaching, but they were unaware of just how much students would actually affect their instruction. Maggie and Tami did not realize the importance of the students' role in shaping the type of instruction until they had actually experienced teaching in a classroom. Their view of a student centered approach to science teaching developed over the course of the teacher preparation program.

The inclusion of students into Maggie's philosophy on teaching was apparent during the initial interview. "I think the best way to teach is going to depend on your students" (Initial Interview, 10/12/96). Even though she realized the importance of the student component in teaching, Maggie didn't fully understand what it would mean to her teaching. Maggie had determined that students' prior knowledge could direct her instruction. One reason Maggie was able to suggest a student led instructional approach was that she was confident in her physics content area of linear motion. For example, she realized that the teacher in the vignette had not properly taught the concept of acceleration. Maggie believed that the introduction of the concept deceleration by a student would not be appropriate at this time. She believed that the students did not understand acceleration, and the introduction of a new term would confuse the students even more.

> But again, if they're having trouble with acceleration, I wouldn't want to go into deceleration because it's coming at a problem...it's the same problem, but it's coming at it from a different angle. So I think I might wait on it depending on how well I felt they were getting it. (Vignette A4)

Maggie was able to focus her suggestion on the students because she had already developed a solid foundation of physics content knowledge.

During her student teaching field experience, Maggie had an opportunity to reflect on students' prior knowledge of gas laws, and consider how their conceptual understanding would influence her teaching in physics class.

> They weren't having questions, they were doing their problems OK. Everything seemed to be going OK. And I didn't notice that I jumped ahead. So if I didn't notice it then with a subject that was not as familiar to them, now you're getting into trials on Boyle's Law, which they've already had in chemistry and physical science. This should just be review for them. They all seem to be on the ball with it, too. I knew I could combine those. (Maggie and Mr. Bently interview)

Maggie based her subsequent instruction on her belief that students should have learned the concept of Boyle's law in previous classes. She used this information to develop her lesson plans. Mr. Bently, the cooperating teacher, confirmed that content knowledge and knowledge that certain concepts were taught in previous classes were imperative in developing her lesson plans.

> We haven't gotten to the ideal gas law; that's coming up. But we've gone all through , Boyle's Law, and a lot of combination of those. So since she knows that I've done that this year, she knows exactly when we did it last year this same way. So she might take into consideration, I think; except remembering more than we really needed. (Mr. Bently interview)

A major component of Maggie's shift from a teacher centered focus to a student centered focus was an emerging awareness that students' learning styles and understanding of concepts might affect her instructional method. In the initial interview Maggie mentioned that students' learning styles were different, and she would possibly alter her pedagogy.

> There are a variety of things that you can do to, 1) help reach different students because they all learn differently...because sometimes they may not get one thing one way but does it as another. And another concept that might get it the first way, but not the second. So you have to look very carefully at both your students and your content before you can really say, my own teaching experience is cooperative learning. (Initial Interview, 10/12/96)

In response to Vignette A Maggie realized that Mrs. Johnson, the teacher in the vignette, was not aware that her actions might have effected other students. "And didn't stop to consider that not all of her students can learn the way she's teaching, but she didn't seem to be concerned that there might be other kids in the class feeling this way, too" (Vignette A2). Maggie believed that Mrs. Johnson should have altered her instructional method to match the students' various learning styles.

At the end of the science curriculum class, Maggie was more keenly aware of how students' understanding of concepts might directly affect her instructional method. In Maggie's fourth response to Vignette A, she mentioned that knowledge of students' misconceptions would help her choose an appropriate instructional method.

> I think I would want to go over their questions, what they turned in at the end of class. And see where, OK, let's look at how they learned velocity and is there anything we need to correct. Are there any misconceptions in there? That needs to be fixed before this goes any farther. (Vignette A4)

Maggie's concern with the vignette was that the content was not taught in a way that took into account students' misconceptions and questions. Maggie's development of PCK was exemplified by the fact that her pedagogy altered after she had developed knowledge of students.

Tami originally saw herself as a lecturer. Her shift towards a student centered teaching philosophy began once she started her education classes, and continued during her student teaching field experience. Tami's knowledge of her students involved recognizing their physics misconceptions and anticipating possible mathematical difficulties for different concepts (Field notes, 5/2/97). For example, Tami had introduced and worked some sample problems for students on the conversion from Celsius to Fahrenheit and vice versa. For her review the next day, she made some adjustments to her instructional method by explaining the mathematical steps to the students while she was explaining the concept.

> I've seen them doing their math before. Just from working with them. I mean I had no clue when I walked in this room that they wouldn't be able to do it. But when I was helping Ms. White when she was doing their power, and they can't solve...they're solving for time, they...do I multiply or divide? They have no clue how to do it. And they can't remember three problems later how to do it. (Vignette B3)

Tami's student centered approach to teaching involved knowing possible or foreseeable mistakes and/or misconceptions that students would make. As Tami came to know her students, and their strengths and weaknesses, she changed her instructional method to include a step by step explanation of the math involved in solving homework problems. Without a solid foundation of physics content knowledge, Tami would not have been able to know the students' misconceptions and then alter her pedagogy.

Both Maggie and Tami shifted to a more student centered approach to teaching science. Maggie developed a well-defined image of how to incorporate students into science teaching. Her development of a student-centered approach was reflected in her increased awareness that students might affect her teaching methods. She also developed a sense of concern and interest in her students' lives. Tami believed that "knowing" her students would help her teach. Tami's shift was also characterized by a growing understanding that students' learning styles would affect her teaching style. Both participants needed content knowledge and knowledge of students before they felt they could teach effectively.

Development of Pedagogical Content Knowledge was Complex and Non-linear. There are many factors that influenced the participants' PCK development. By analyzing the difficulties of developing different types of PCK, it was determined that PCK development was complex and non-linear. Maggie and Tami were both able to develop topic-specific pedagogical content knowledge (TSPCK). Their development paralleled the concepts and topics taught during their student teaching field experience. Prior to Maggie and Tami's experiences teaching the concepts of heat energy and temperature found in Vignette B, their suggestions of how to teach these concepts were very general in nature. Once they had the opportunity to plan, teach, and work with students, Maggie and Tami suggested detailed examples, analogies, laboratories and demonstrations. The use of examples, analogies, and demonstrations was what Shulman (1986) called pedagogical content knowledge; "the most useful forms of representations of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations" (p. 9).

Maggie's TSPCK in relation to heat energy and temperature did not develop until she began to teach a unit on thermodynamics. For example, in Maggie's first response to Vignette B, she was unsure of any specific ways to teach thermodynamics.

> I don't know. Well, I'd have to go back and remind myself of all this stuff anyway, just because I...it's been a while since I've talked about it [thermodynamics] in any of the classes I've taken, but I would try to make definite connections though between what the technical names are for things, and what we commonly know them as. (Vignette B1)

Once she began to develop a unit on heat and the laws of thermodynamics for her physics class, Maggie was able to suggest several activities in response to Vignette B. Maggie's development of TSPCK for heat and temperature was facilitated by her familiarity with the physics chapter (Field notes, 2/12/97-2/26/97). The chapter introduced concepts of heat and temperature, continued with heat capacity and heat energy, and concluded with heat expansion. After teaching students the concepts in the chapter, Maggie was able to make specific comments about how to teach the concepts found in Vignette B. For example, Mr. Jackson used an analogy of a waterfall exemplifying heat energy flowing from one place to another. Maggie was able to critique the analogy based upon her experiences teaching the concept of heat transfer to her students.

> The analogy with heat being like a waterfall...I think is a good one. But I think he introduced it too soon. He hadn't defined heat as being a flow of thermal energy from one place to another. So I think it was incomplete, too. Not because of what he said, but

> rather because it came to soon. He's comparing heat to the flow of water and yet he hasn't defined what he did correctly. So I think it's, it is good, but not yet. (Vignette B4)

Maggie's concern was not that the analogy was incorrect; rather, she believed that it was used at an inappropriate time during the lesson. Maggie's development of TSPCK involved knowing about the appropriate time and purpose to use analogies during instruction. By the end of her student teaching field experience, Maggie had developed the ability to determine whether a topic-specific analogy was used correctly and effectively.

Maggie was also able to suggest a demonstration that would help explain the concept of heat transfer. Having recently taught the concept of specific heat to her students, Maggie was able to make a specific suggestion in relation to a situation in Vignette B. Maggie suggested that a laboratory in which a piece of brass at a certain temperature was placed in a specific amount of water, would demonstrate the concept of heat flow.

> Well, what we've been doing is questions, qualitative questions. Define heat, define temperature? Stuff like that. And then problems. The problems usually had to do with using the equations this equals something. He defined heat or specific heat or final temperature. And then we did a lot of law of heat exchange problems. OK, if you have this scenario, these two...the water's going to change at this temperature, you put in something else, it's at this temperature, what's the final temperature? Or it goes to this final temperature, what's the specific heat of the brass that you put in it, type of questions. (Vignette B4)

Maggie's suggestion for topic-specific analytical reasoning problems was in response to her belief that teaching should involve more than just working problems. The inclusion of topic-specific problems or questions demonstrated her TSPCK in thermodynamics. Maggie's development of TSPCK involved learning examples from the physics textbook, remembering activities from her experiences as a student, and implementing demonstrations and activities mentioned by her cooperating teacher.

In Tami's first response to Vignette B, she was unable to suggest an appropriate way to teach the concept of heat and temperature. She did note that as a teacher she would use the students' thoughts and ideas as a basis for her lesson. Although Tami knew there was a misconception about heat and temperature in Vignette B, she was unable to clarify its exact nature. She was unable to suggest a specific activity that might be used to challenge students' misconceptions.

During her second response to Vignette B, Tami still did not have any detailed suggestions for distinguishing between heat and temperature. "I'll have to be honest I haven't really looked through this part of the material. So I don't really know" (Vignette B2). Part of Tami's anguish in analyzing the vignette came from not knowing the content well enough to develop ideas or make suggestions. Tami's method of teaching and developing activities, laboratories, examples, or problems was to rely on preexisting sources such as teacher's editions of textbooks. "Right now I'd photocopy. I'm not comfortable enough to create my own laboratories. I modify sometimes but I don't" (Vignette B2). Part of Tami's development of TSPCK was learning how to create, adapt, or locate ideas for instruction from external sources.

By the time Tami analyzed Vignette B for the third time, she had already been teaching heat energy and temperature topics to her physical science classes. With the added experience of preparing lesson plans, explaining concepts, and observing students work, Tami was able to analyze the vignette in greater detail, and make suggestions about possible ways to teach the concepts of heat energy and temperature.

> I'm learning, like going back what I would now if I could is...go back and do the one like he did with two different amounts of water, and then go back and say, OK, well explain this in heat energy. And then go back and say, Well, we've done it, now let's talk about it. And see if we can connect up that way. (Vignette B4)

Tami thought the heat/temperature demonstration used by Mr. Jackson in the vignette was appropriate. The demonstration involved the determination of which beaker of water had the most energy and why; the beakers had two different masses of water at the same temperature. In order to improve on the demonstration, Tami realized that a better explanation and discussion was needed. Tami's suggestion involved using two different amounts of water at two different temperatures to show heat transfer. Her suggestion represented TSPCK development. She later explained in the same vignette analysis the intricacies of doing this actual laboratory in her class.

> I was when we heated two different amounts of water and we talked about how the heat in them for three minutes and took the temperature, then you heated the large one for three minutes and took the temperature, and of course, it was less. So you had to heat it longer to get to the same. And you come to your temperatures and heat energy. And how the bigger one contained more heat energy because they had more mass and connected it that way. (Vignette B4)

Tami was unable to suggest this laboratory before actually teaching a unit on thermodynamics in one of her classes. Tami's TSPCK development was facilitated by her immersion in the classroom teaching experience.

Maggie's only demonstration of the development of DSPCK was found in her last response to Vignette B. Maggie focused on the sequence of thermodynamics concepts that Mr. Jackson had used when teaching in Vignette B. The sequencing of topics can be considered domain-specific, because the topics, themselves, are domain-specific. An awareness of an appropriate sequence of topics and methods of instruction in a curriculum would indicate development of DSPCK. In Maggie's fourth response to Vignette B, she voiced her concern about the amount of content and the speed of content presentation.

> I think he gave them too much information too fast. And then...here he was talking about conservation energy, he was talking about macroscopic levels, which they may or may not understand anyway. He talked about, let's see, conservation matter, conservation energy, efficiency, losing heat, and transfer of energy all in what, on paper, turns out to be only one paragraph. And that's just, that's too much. (Vignette B4)

Maggie had another opportunity to develop DSPCK when she taught astronomy in both Earth science and physics. She was unable to take advantage of this opportunity. Maggie's teaching style for Earth science and physics were very similar (Field notes, 2/14/97-2/26/97). The similarities in teaching styles constrained her ability to differentiate the content for the different levels of students. This might be attributed to Maggie's attempts to develop herself as a teacher, rather than a teacher of physics, or a teacher of science. The fact that Maggie may have developed as a teacher rather than a physics teacher was illustrated in all of her general comments and suggestions during her vignette responses (Vignette B1-4). She talked about teaching physics, but she realized that she had to learn to teach. Maggie showed little development of DSPCK.

Tami was in a different situation than Maggie. Tami's cooperating teacher taught physics using a lecture and problem working orientation with little emphasis on hands-on activities. At first Tami wanted to diverge from this teaching style, and create one that was personally more compatible. She soon learned that knowing the content would impede her ability to develop a unique and personal teaching style for physics. "I think you have to have the content knowledge going in. I mean, that's just...you've got to learn that in your science classes. You've got to know your content" (Vignette B3).

Maggie and Tami developed little perceivable DSPCK. One possible factor that effected development of DSPCK was the fact that Maggie and Tami only taught one class of physics. They were not able to reflect on their teaching, and alter or improve their methods of instruction for another physics class. One problem with analyzing data for this particular theme was categorizing what evidence constituted DSPCK. Science content-specific teaching strategies have been well documented (e.g., Magnusson, Krajcik, & Borko, 1997), but domain-specific strategies have not been documented. It might be inferred that DSPCK can only develop in experienced teachers who have learned their content areas well enough and have learned to translate, using multiple methods, the content to students' levels of understanding.

Discussion

The development of PCK does not occur suddenly. There is no one event, activity, or phenomenon that, in and of itself, causes a prospective teacher to develop PCK. Rather, the development is gradual and progressive. DeRuiter (1991) suggested that "learning to teach" was done "through qualitative transformations or phases," rather than a great and sudden transformation or event supports this view. There are no epiphanies associated with development of PCK. Rather, the development of PCK occurs in phases that are neither sequential nor linear. The six phases determined to be associated with the development of pedagogical content knowledge in this study are:

1. Prospective science teachers were able to integrate the curricula, textbooks, and resources into coherent lesson plans.
2. Prospective science teachers showed an increased differentiation in how they viewed the teaching of physics or chemistry.
3. Prospective science teachers encountered a perturbation that created some sort of dissonance in their beliefs of how to teach chemistry or physics.
4. Participants had the opportunity to reflect on their beliefs, the content knowledge, and any perturbations.
5. Prospective science teachers wrestled with conflicting beliefs by instructing outside of the cooperating teacher's paradigm when given the opportunity.
6. Prospective science teachers integrated, modified, or developed new personal theories that took into consideration many aspects of the classroom learning environment.

Prospective teachers may begin development of PCK at different phases due to their knowledge of content, students, and pedagogy. Depending on the teacher preparation program and student teaching experiences, different phases could occur at different times in prospective teachers' development. Once development has begun, prospective teachers may go through the phases at different rates.

The overall process of development within these phases is symbiotic. When one phase has been completed, one or two other phases have already begun. The knowledge gained while developing with respect to one phase is dialectically related to knowledge and experience developed in another phase. Part of development requires revisiting a phase for further development. A useful analogy for this process involves M. C. Escher's drawing of the perpetual staircase. In this drawing, the actual staircase has four flights. The staircase for PCK development has six flights, representing the six phases of PCK development. As with M. C. Escher's diagram, people walk up and down the staircase in a never-ending journey. The up and down movement symbolizes the interrelated and symbiotic nature of the stages. Another aspect of Escher's diagram is the fact that people are ascending and descending on the top, bottom, and sides of the staircase. This represents the different pathways prospective teachers could take in the development of their PCK.

The phases are not linear stages of development as with Piaget's stages of mental or cognitive development. Piaget (1964) described the mental or cognitive development of children as occurring through four sequential stages. A stage had to be finished before the next stage of development could occur. In the model developed for this study, the phases can occur independently of each other or simultaneously. Phases 1-3 could begin during a science methods class, and continue to develop throughout a teacher's career. Phases 4-6 would most likely occur once the prospective teacher had begun his/her practicum or student teaching field experience, and also continue to develop throughout a teacher's career.

The phases, substantively, do not entirely resemble the content of Piaget's stages of development. Piaget (1964, 1980) wrote about accommodation, assimilation, disequilibrium, schemes, universality, and adaptation as key aspects of cognitive development. The phase model does not incorporate any of these ideas. One area of commonality is the idea that learners go through stable periods of development which Piaget termed equilibrium. In the development of PCK, prospective teachers experience times of confidence and serenity in their teaching. The phase model does not include the idea of schema or internal functions of individuals, except with respect to their beliefs about teaching and learning science.

The development of these phases may begin in the science methods and/or curriculum class, expands during the practicum and student teaching field experiences, and continues throughout the professional life of a teacher. For example, the science curriculum professor had his students review textbooks for a particular domain during his science curriculum class (Field notes, 10/7-10/8/96). The prospective teachers noticed various aspects that would be helpful to them as teachers such as practical examples, analogies, cartoons depicting concepts, concept maps, and supplemental resources. The realization of the practical use of textbooks was revisited continuously as the prospective teachers developed lesson plans, taught concepts found in textbooks, and led students through textbook based activities and laboratories. Eventually, as practicing teachers, their development will continue to grow as they encounter opportunities to change or add to their personal theories of teaching. Textbook adoption and national or district curriculum standards integration are two possible events that might provide further opportunities for personal theory modification.

Conant (1963) attacked professional education classes for the lack of a single construct or unifying idea to lead teacher education programs; "professors of education have not yet agreed upon a common body of knowledge that they all feel should be held by school teachers before the student takes his first full-time job" (p. 9). The NSES recommended the creation of professional development standards with PCK being a standard for science teacher development. Shulman (1986,1987) first introduced the term pedagogical content knowledge. Shulman (1987) suggested that teacher education should undergo a reform so that the knowledge bases of content and pedagogy were combined in a more cohesive and understandable manner. Shulman defined PCK to distinguish between a content specialist and a science teacher. The meaning and intention behind the introduction of PCK has been expanded to include more than just the combining of two knowledge bases; it has come to include different aspects of teaching and learning, and has been applied to science teaching and learning (Doster, Jackson & Smith, 1994; Magnusson, Krajcik, & Borko, 1997). Pedagogical content knowledge as developed in preservice physics teachers in this study, represents a viable and coherent knowledge base for science teacher education.

The underlying and unifying construct of a knowledge base for professional teaching included "not only knowledge but also insight into how this knowledge is properly related to practice" (Tom & Valli, 1990, p. 389). The participants in this study realized and expressed the importance of the practical experience to their development. Johnston (1992) argued for the inclusion of teachers' and prospective teachers' practical knowledge in teacher education programs. The practical knowledge that was found in the development of PCK in this study contained many different characteristics.

Some researchers have equated practical knowledge with craft knowledge (Grimmet & MacKinnon, 1992; Leinhardt, 1990). There are many similarities, and few differences. Carter (1990) stated that PCK was more grounded in a discipline than practical knowledge. Thus, the results of this study imply that practical knowledge should be equated with general PCK. Even though Grimmett and MacKinnon (1992) stated that PCK was a component of craft knowledge, findings in this study support the view that craft knowledge can be equated with domain-specific PCK.

Many researchers have described and defined PCK incorporating different attributes or characteristics. The various descriptive accounts and definitions did not place any significance on the development of PCK. Cochran, King, and DeRuiter (1991) created the only diagram that included an example of the development of PCK. The empirically derived diagram in Figure 1 details a hierarchical organizational structure for PCK and its characteristics. The central location of PCK signifies its importance. The surrounding attributes are all connected, representing the diagram's integrated nature.

Figure 1. Diagram of pedagogical content knowledge attributes

The hierarchical organizational structure suggests that a strong content background is essential to the development of PCK. The content knowledge can be general, domain specific or topic specific. As illustrated in Figure 1, the second most important attribute a science teacher needs in developing PCK is knowledge of students. Once the teacher or prospective teacher understands or realizes the importance of the student component to teaching then the other attributes or characteristics of PCK can be learned or developed. This hierarchical structure was supported by empirical data from this study; thus implying a taxonomy of PCK.

One interesting aspect of the diagram/taxonomy is the significance of content knowledge. Without content knowledge, a teacher may not develop the ability to instruct science on a high school level. On the other end of the spectrum, elementary teachers might have little science content knowledge, but have significant knowledge of science process skills (Martin, 1996). Content knowledge should progressively become more detailed and deeper in the middle school. At the secondary or high school level, science teachers must have a deep understanding of their content, but the knowledge is not fixed in such a manner that the content topics cannot be altered or re-examined for instruction.

Another interesting aspect of the taxonomy in Figure 1 is the placement of pedagogical knowledge. Pedagogical knowledge is not as important in this hierarchical taxonomy as in other taxonomies (Morine-Dershimer & Kent, 1997; Shulman, 1987; Tamir, 1987). In this study, the student component appears to have more significance than previous taxonomies have attributed to it. A knowledge of the students includes understanding possible student errors and misconceptions. Student errors and misconceptions are more easily recognizable when the teacher knows the content topics and concepts. When a teacher realizes the impact he/she can make on students and that students have different learning styles, he/she might develop and apply specific pedagogy appropriate to the student, domain, or concept. While the ultimate goal is for students to learn science, the focus of the taxonomy is on how teachers develop PCK. The focus shifts again to the student once instruction begins.

Based upon the results of this study and the structuring of the taxonomy of PCK attributes, an operational definition is warranted. Pedagogical content knowledge is the ability to translate subject matter to a diverse group of students using multiple strategies and methods of instruction. The term translate is used instead of transform (Shulman, 1987), because content is adjusted to fit the understanding of the students. For example, just as Spanish words are translated into English, science concepts are translated into understandable units of meaning for students. When a person translates a phrase or idea from one language to another, the translator must know; the audience's level of understanding, the correct words to use, the order in which to place words, hand gestures and examples that would facilitate understanding, and cultural items which might help in the translation. When the principles of translation are applied to science, the teacher must have the associated knowledges of a translator (knowledge of students, content, pedagogy, context, and environment) to properly convey his/her message (physics).

The eight outlying attributes of PCK are not arranged in a hierarchical manner, because they can be developed and understood by the teacher at any time during their teaching career. The attributes are inter-related; thus, the development of one can simultaneously trigger the development of others. For example, pedagogical knowledge and assessment are usually learned in methods classes. The knowledge of when, how, and why assessment is used combines two attributes. When the prospective teacher experiments with performance assessment, he/she will probably integrate her knowledge of instructional methods to make sure the assessment device is fair (Payne, 1992).

The hierarchical structure of the taxonomy with the eight outlying attributes implies that a foundation consisting of two knowledges should be acquired before the other attributes are developed. The interconnected nature of the taxonomy implies that knowledge of content and students can be relearned continuously, depending on the level and type of student or content. The interconnectedness of the taxonomy promotes the idea of a teacher as a life long learner. It might be possible to develop all attributes in a science methods and curriculum class, but the usefulness, impact, and understanding will not be fully realized or integrated until a teacher has acquired classroom experience within a content domain (Clermont, Borko, and Krajcik, 1990; Tuan, Jeng, Whang, & Kaou, 1995).

Implications for Science Teacher Education

Secondary science education programs should focus on developing topic-specific PCK in prospective teachers. By focusing on topic-specific examples, laboratories, and demonstrations, prospective teachers can focus and develop specific teaching strategies for physics. As initiated by Project 30 and in accordance with findings in this study, universities should try to bridge the gap between the colleges of arts and sciences and education. The bridging of these traditionally diverse knowledge bases would help prospective teachers understand how PCK could help them view science teaching and learning.

Craft knowledge in this study was used as a theoretical framework. More research is needed to study the possible integration of craft knowledge with science education. Pedagogical content knowledge could provide the catalyst for the integration. Experience in the classrooms was considered a major factor in the development of pedagogical content knowledge in this study. Examining the relationship between experience, pedagogical content knowledge, and craft knowledge could allow researchers to explore the possibilities of a different theoretical framework in science education.

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