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Conceptualization of Pedagogical Content Knowledge

Li Xingshan and Pan Yaotian

Central Southern University, China

Abstract: The purpose of this study was to rethink the conceptualization of pedagogical content knowledge based on our descriptive research findings and to show how this new conceptualization helps us to understand teachers as professionals. This study was a multiple case study grounded in a social constructivist framework. Data were collected from multiple sources and analysed using three approaches: (a) constant comparative method, (b) enumerative approach, and (c) in-depth analysis of explicit PCK. The results indicated that (a) PCK was developed through reflection-in-action and reflection-on-action within given instructional contexts, (b) teacher efficacy emerged as an affective affiliate of PCK, (c) students had an important impact on PCK development, (d) students' misconceptions played a significant role in shaping PCK, and (e) PCK was idiosyncratic in some aspects of its enactment. Discussion centres on how these five aspects are related to teacher professionalism.

Introduction

Many studies have suggested the centrality of teachers within the gamut of educational processes (Calderhead *1996*). Armed with this growing awareness, researchers have directed increased attention to teachers' knowledge and how it is developed (Borko and Putnam *1996*; Calderhead *1996*). Much of this interest was stimulated by Shulman's (*1986*) report that introduced the concept of pedagogical content knowledge (PCK) as a distinctive body of knowledge for teaching. PCK is an acknowledgement to the importance of the transformation of subject matter knowledge per se into subject matter knowledge for teaching.

By and large, PCK has been described as the knowledge used to transform subject matter content into forms more comprehensible to students (Geddis et al. *1993*; Grossman *1990*; Marks *1990*; Shulman *1986*, *1987*). In this regard, the development of PCK involves a dramatic shift in teachers' understanding "from being able to comprehend subject matter for themselves, to becoming able to elucidate subject matter in new ways, reorganize and partition it, clothe it in activities and emotions, in metaphors and exercises, and in examples and demonstrations, so that it can be grasped by students" (Shulman *1987*, p. 13). What distinguishes novice from expert teachers is, then, possession of such knowledge, "the capacity of a teacher to transform the content knowledge he or she possesses into forms that are pedagogically powerful and yet adaptive to the variations in ability and background presented by students" (Shulman *1987*, p. 15). In this respect, PCK has been identified as a knowledge base teachers should possess in educational reform documents (e.g., American Association for the Advancement of Science [AAAS] *1993*; National

Research Council [NRC] 1996).

Although Shulman originally fashioned a definition, individuals within any group of educational stakeholders, researchers, teacher educators, teachers or others, are likely to interpret the nature of PCK differently thus engendering a variety of meanings. Beyond the issues of interpretation, the high level of specificity of PCK with respect to instructional variables such as students' characteristics, subject matter, contexts, and pedagogy (Cochran et al. 1993; Hashweh 2005; Loughran et al. 2006) makes the task of defining PCK more challenging. Consequently, the amorphic nature of PCK causes difficulty in its explicit use as a conceptual tool (Magnusson et al. 1999; Veal and MaKinster 1999). In other words, it has been difficult to portray a clear picture not only of how to scaffold PCK development in teachers but also of how to assess it once constructed. With this in mind, the primary purpose of this study was to re-examine the construct of PCK based on our empirical research with experienced high school teachers. In doing so, we hoped to gain a better understanding of PCK and further facilitate communication among educational researchers, teacher educators, and teachers by eliciting agreement about the definition of this frequently named but idiosyncratically understood concept.

Theoretical Framework

To set forth the conceptual aspects of PCK as have been identified through research, we first conducted a comprehensive literature review and then examined the relative significance of those aspects within and between those research studies.

Knowledge Bases for Teaching

The first literature considered was that dealing with the characterization of knowledge bases for teaching. This literature, in some cases, predates Shulman's work on the subject (see for instance, Elbaz 1983; Leinhardt and Smith 1985). Other papers were published concurrently (Tamir 1988; Grossman 1990) with Shulman but the Shulman articles (Shulman 1987; Wilson et al. 1987) are distinguishable due to the extensive list of separate knowledge bases included (e.g., pedagogy, educational goals and objectives, subject matter content, curriculum, context, knowledge of students, other content matter, and PCK) within the conception of teacher knowledge.

While researchers have differed in their characterization of the relationship between various sub-domains of teacher knowledge, four commonalities have consistently appeared: pedagogical knowledge, subject matter knowledge, PCK, and knowledge of context. Figure 1 (modified from Grossman 1990) provides an illustrative overview of the four commonalities.

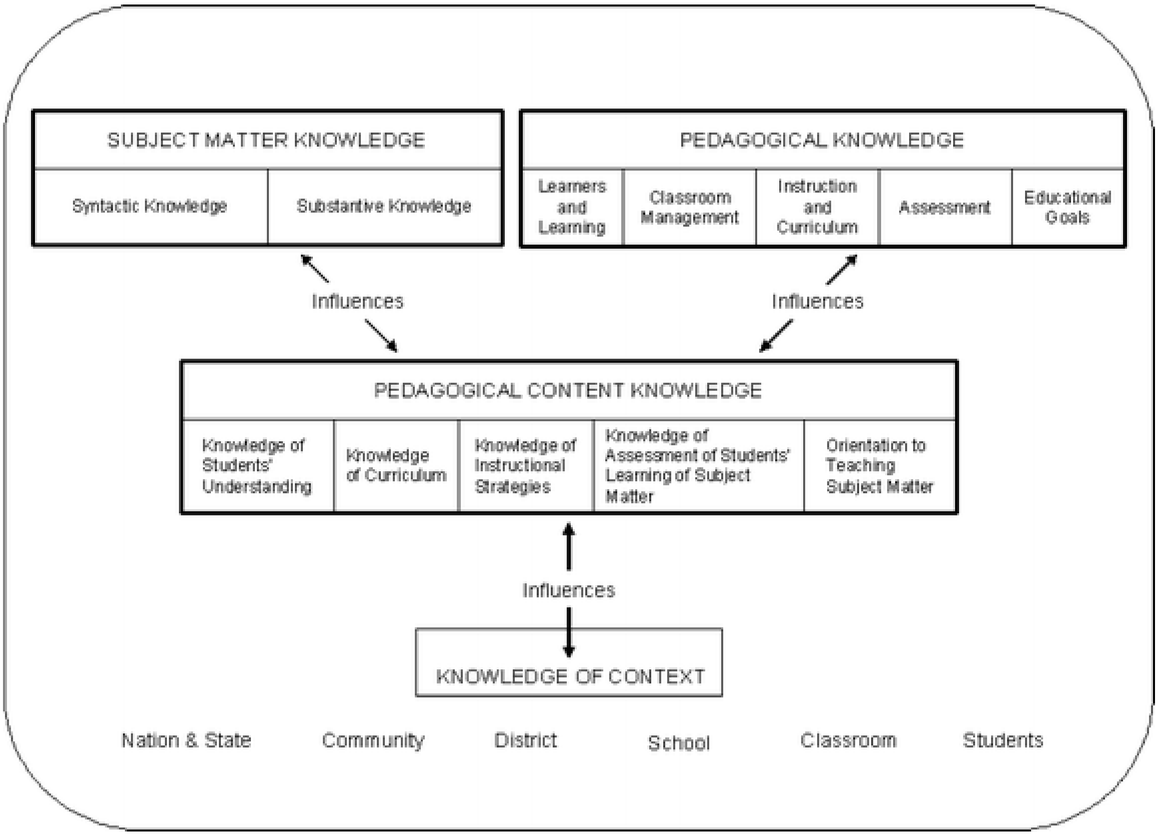

Fig. 1 Knowledge bases for teaching [modified from Grossman (*1990*)]

Our aim is to put forward a model of teacher knowledge that is richly contextualized in the practice "from which it arose and in which it is used" (Borko and Putnam *1996*, p. 677). Further, this research attempts to represent all domains of teacher knowledge as embedded in the larger milieu. Using this conceptualization of knowledge bases for teaching, the definition of PCK is discussed in the next section.

Conceptions of Pedagogical Content Knowledge

Shulman (*1987*) defined PCK as follows in his presidential address to the AERA:

It represents the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to the diverse interests and abilities of learners, and presented for instruction (p.8).

This definition implies that "PCK is both an external and internal construct, as it is constituted by what a teacher knows, what a teacher does, and the reasons for the teacher's actions" (Baxter and Lederman *1999*, p. 158). Hence, PCK encompasses both teachers' understanding and their enactment.

A growing number of scholars have worked on the concept (e.g., Geddis et al. *1993*; Grossman *1990*; Hashweh *2005*; Loughran et al. *2006*; Marks *1990*; Magnusson et al. *1999*; Van Driel et al. *1998*) since its inception. One of the common ways for the researchers to identify PCK has been to modify Shulman's (*1986*, *1987*) definition. For example, Geddis et al. (*1993*) defined PCK as knowledge that played a role in transforming subject matter into forms that are more accessible to students. Carter (*1990*) viewed PCK as what teachers know about their subject matter and how they transform that knowledge into classroom curricular events.

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Taken together and given the caveat of these variations, it is transformation of subject matter knowledge for the purpose of teaching that is at the heart of the definition of PCK. In other words, it is commonly stated that PCK is used to adapt subject matter knowledge for pedagogical purposes through a process Shulman (*1987*) called "transformation," Ball (*1990*) labelled "representation," Veal and MaKinster (*1999*) termed "translation," Bullough (*2001*) named "professionalizing," and Dewey (1902/*1983*) entitled "psychologizing."

Another pervasive way of conceptualizing PCK was to identify the components constituting PCK and view PCK as an integration of those components. Table 1 summarizes different scholars' conceptualizations of PCK in this way.

Table 1 Components of pedagogical content knowledge from different conceptualizations [extended from Van Driel et al. (*1998*)]

Scholars	**Knowledge of**							
	Purposes for teaching a subject matter	**Student understanding**	**Curriculum**	**Instructional strategies and representations**	**Media**	**Assessment**	**Subject matter**	**Context**
Shulman (*1987*)	D	O	D	O			D	D
Tamir (*1988*)		O	O	O		O	D	
Grossman (*1990*)	O	O	O	O			D	
Marks (*1990*)		O		O	O		O	
Smith and Neale (*1989*)	O	O		O			D	
Cochran et al. (*1993*)		O		N			O	O
Geddis et al. (*1993*)		O	O	O				
Fernandez-Balboa and Stiehl (*1995*)	O	O		O			O	O
Magnussonet al. (*1999*)	O	O	O	O		O		
Hasweh (*2005*)	O	O	O	O		O	O	O
Loughran et al. (*2006*)	O	O		O			O	O

D Author placed this subcategory outside of PCK as a distinct knowledge base for teaching; *N* author did not discuss this subcategory explicitly (Equivalent to blank but used for emphasis); *O* author included this subcategory as a component of PCK.

As illustrated in Table 1, the scholars elaborated and expanded on Shulman's (*1986*, *1987*) concept mainly by identifying the constituent components based on their beliefs or the findings from empirical studies. The differences among the scholars occurred with respect to the components they integrate in PCK, and to specific labels or descriptions of these components. However, most scholars agreed on Shulman's (*1986*) two key components of PCK (see Table 1): (a) knowledge of instructional strategies incorporating representations of subject matter and responses to specific learning difficulties and (b) student conceptions with respect to that subject matter.

In the end, reviews and analysis of the literature on PCK contributed to what we believe to be a comprehensive working definition of PCK for this study: PCK is *teachers' understanding and enactment* of how to help a group of students understand specific subject matter using multiple instructional strategies, representations, and assessments while working within the contextual, cultural, and social limitations in the learning environment.

Along with the working definition of PCK, we identified five components of PCK for science teaching mainly drawn from the work of Grossman (*1990*), Tamir (*1988*), and Magnusson et al. (*1999*): (a) orientations to science teaching, (b) knowledge of students' understanding in science, (c) knowledge of science curriculum, (d) knowledge of instructional strategies and representations for teaching science, and (e) knowledge of assessments of science learning. Although we acknowledged that they are not mutually exclusive, we regarded them as distinct components for the development of assessment tools for PCK.

Within our research, we organized the five components of PCK into a pentagonal form with PCK in the centre. This served as a heuristic devise and as an organizational tool for the observable components of PCK. Placing PCK at the centre was intended to indicate its potential development from any of these five components. This model contained subcomponents which indicated potential sources within an instructional setting (This is explained in detail in the next section.).

On one hand, the development of one component of PCK may simultaneously encourage the development of others, and ultimately enhance the overall PCK. On the other hand, PCK for effective teaching is the integration of all aspects of teacher knowledge in highly complex ways. Thus, lack of coherence among the components would be problematic within an individual's developing PCK and increased knowledge of a single component may not be sufficient to stimulate change in practice. What follows is the description of each component of PCK with emphasis on how these informed the conceptual framework for the data analysis.

Orientations to Teaching Science This component refers to teachers' beliefs about the purposes and goals for teaching science at different grade levels (Grossman *1990*). Since the transformation of teacher knowledge from other knowledge domains into PCK is not a straightforward task but an intentional act in which teachers choose to reconstruct their understanding to fit a situation (Magnusson et al. *1999*), orientations to teaching science influence PCK construction by serving as a concept map that guides instructional decisions, the use of particular curricular materials and instructional strategies, and assessment of student learning (Borko and Putnam *1996*).

For this study, the nine orientations toward teaching science identified by Magnusson et al. (1999) were adopted: process, academic rigor, didactic, conceptual change, activity-driven, discovery, project-based science, inquiry, and guided inquiry.

Knowledge of Students' Understanding in Science To employ PCK effectively, teachers must have knowledge about what students know about a topic and areas of likely difficulty. This component includes knowledge of students' conceptions of particular topics, learning difficulties, motivation, and diversity in ability, learning style, interest, developmental level, and need.

Knowledge of Science Curriculum This refers to teachers' knowledge about curriculum materials available for teaching particular subject matter as well as about both the horizontal and vertical curricula for a subject (Grossman 1990). This component is indicative of teacher understanding of the importance of topics relative to the curriculum as a whole. This knowledge enables teachers to identify core concepts, modify activities, and eliminate aspects judged to be peripheral to the targeted conceptual understandings. Geddis et al. (1993) called this understanding "curricular saliency"（课程的卓越） to point to the tension between "covering the curriculum" and "teaching for understanding."

Knowledge of Instructional Strategies and Representations for Teaching Science This component consists of two categories: subject-specific strategies and topic-specific strategies (Magnusson et al. 1999). Subject-specific strategies are general approaches to instruction that are consistent with the goals of science teaching in teachers' minds such as learning cycles, conceptual change strategies, and inquiry-oriented instruction. Topic-specific strategies refer to specific strategies that apply to teaching particular topics within a domain of science.

Knowledge of Assessment of Science Learning Novak (1993) stated, "Every educational event has a learner, a teacher, a subject matter, and a social environment. I would like to suggest a fifth element – evaluation" (p. 54). In accordance with this, knowledge of assessment is an important component of PCK. This component is comprised of knowledge of the dimensions of science learning important to assess, and knowledge of the methods by which that learning can be assessed (Tamir 1988). This component includes knowledge of specific instruments, approaches, or activities.

Materials and Methods

Research Design

This study was a multiple case study of three experienced chemistry teachers who were working in the same high school, Chattahoochee River High School (CRHS; pseudonym). All of them are female and White. Table 2 presents background information about the participants. For confidentiality, all were given pseudonyms.

Table 2 Background information of participants

	Amy	**Lucy**	**Jane**
Education	B.S./M.Ed.	B.S./B.Ed./M.Ed.	B.Ed./M.Ed./Specialist
Science	Physics and	Physics and	Biology and Chemistry

	Amy	Lucy	Jane
background	Chemistry	Chemistry	
Teaching years	21 years	11 years	8 years
Teaching subjects	Honors chemistry	Advanced placement chemistry	Honors chemistry
	College preparatory chemistry	Gifted chemistry	College preparatory chemistry

Data Collection

As Kagan (1990) argued, the complexity of teachers' knowledge cannot be captured by a single instrument. Particularly, assessment of PCK requires a combination of approaches that can collect information about what teachers know, what they believe, what they do, and the reasons for their actions (Baxter and Lederman 1999). In this regard, we collected data from multiple sources including classroom observations, semi-structured interviews, lesson plans, teachers' written reflections, students' work samples, and researcher's field notes. We observed three subject matter units for each teacher using a non-participant observation method. For each unit, at least four class periods were observed. Since we cannot observe everything we want to know, interviews can provide access to the context of teachers' action and what they know. Thus, we also conducted interviews in combination with classroom observations in a semi-structured way. All interviews and observations were audiotaped and transcribed verbatim. The teachers were also asked to write reflections on their teaching. Field notes were recorded by the first author during and after each classroom observation, and a reflective journal was kept throughout the research process.

Data Analysis

The data were analysed through three different approaches: (a) constant comparative method, (b) enumerative approach, and (c) in-depth analysis of explicit PCK. In the constant comparative method, the data analysis focused on the identification of regularities or patterns in interview and observation transcripts through an interactive process during which the data were constantly compared (Charmaz 2000). The two authors independently coded the transcripts and any disagreements were discussed until a consensus was reached. Also, patterns and themes emerging from the data were discussed and refined using investigator triangulation (Janesick 1994).

We also employed the enumerative analysis approach (LeCompte and Preissle 1993) so as to reduce the subjectiveness of qualitative coding and facilitate identifying the characteristics of each teacher's PCK. We first created the "PCK Evidence Reporting Table (PCK ERT)" in which the five components of the pentagon model were presented as categories. For each component, sub categories were developed through a comprehensive literature review described earlier (see Appendix A). Using those categories and sub-categories in the PCK ERT as a pre-established set of codes, the two authors coded together the same observation transcripts again using Atlas.ti, a computer assisted qualitative data analysis software. At the same time, we tallied the occurrences of each sub component in the PCK ERT. In the case that clarification was needed for coding, we referred to pre- and post-observation interviews and written reflections associated with the observation being coded and then made notes in the margins of the PCK ERT. The results from the enumerative approach were compared with and integrated into the results from the constant comparative method in order to provide methodological triangulation (Denzin *1978*).

In order to promote the capture of the evidence of PCK, we analysed teaching segments in depth that revealed PCK explicitly. We first identified teaching segments of explicit PCK from the observation data according to our working definition of PCK and the heuristic model. When explicit PCK was identified, the first author made a detailed description of the segment in three aspects: (1) what the teacher did, (2) why the teacher did what she did, and (3) what the teacher knew. This description was grounded in observation, but supplemented by interviews, written reflections, and the other data sources connected with the teaching segment examined. The second author then reviewed the description and two authors discussed and negotiated any incongruities. The initial inter-rater reliability was 92%. An example of this in-depth analysis of explicit PCK presented in Appendix B.

The data from lesson plans, students work samples, and field notes were analysed through similar procedures. Then, all data from multiple sources were triangulated to ensure the trustworthiness of this study.

Findings

Data analysis revealed five salient features of PCK which complement and add to the current literature. These are: (a) PCK development occurred as a result of reflection related to both knowledge-in-action and knowledge-on-action; (b) teacher efficacy was evident as an affective affiliate of PCK; (c) students influenced the ways that PCK was organized, developed, and validated; (d) teachers' understanding of students' misconceptions was a major factor that shaped PCK in planning, conducting instruction, and assessment; and (e) PCK was idiosyncratic in some of its enactments.

PCK: Knowledge-In-Action and Knowledge-On-Action

PCK was manifested as a feature of knowledge-in-action. This term is defined as knowledge developed and enacted during teaching through "reflection-in-action" (Schon *1983*, *1987*). In particular, PCK as knowledge-in-action became salient in situations where a teacher encountered an unexpectedly challenging moment in a given teaching circumstance. In order to transform the challenging moment into a teachable moment, the teacher had to integrate all components of PCK accessible at that moment and apply them to students through an appropriate instructional response. In this respect, the development and enactment of PCK is an active and dynamic process.

For example, in Lucy's metal lab, students were asked to test as many chemical and physical properties of various metals as possible during the lab. The students boiled, bent, hit, and applied other physical stresses. However, when students hit zinc with hammers, it shattered rather than bending as was expected. In that situation, Lucy was surprised by the outcome and reasoned that the zinc was oxidized and its characteristics significantly changed as a result. She realized that this incident might cause students to develop misconceptions about characteristics of metals. Thus, she decided to have students discuss the incident and then asked, “Why do you think the zinc shattered while the other metals bent when you hit them?” She then ended up leading a discussion about differences between compounds and elements though this was a topic which the students would learn in a later unit. After the class, Lucy reflected on the event:

Zinc is a metal and it shouldn’t shatter...I think a lot of it had kind of oxidized. So I thought that could be a teaching moment. We kind of talked about, when zinc is already in a compound, does it still have the properties of the metal? That brought that concept out. Kids are always thinking that an ionic compound, because...it contains a metal, they think it’ll have all those properties of a metal. And a lot of them think the metals could be brittle. It was interesting to confront those misconceptions through the discussion. (Lucy, post observation interview 1)

This statement implied that Lucy actively integrated her knowledge of subject matter, science curriculum (i.e., the differences between compounds and elements following the properties of metals in science curriculum), and students’ misconceptions associated with metals at the unforeseen moment, and then applied the resulting PCK to the students through instructional strategies such as questioning and discussion. Consequently, she was able to use this challenging event as a conduit to help students arrive at an understanding of the differences between elements and compounds.

PCK was also revealed as a feature of knowledge-on-action; that is knowledge elaborated and enacted through “reflection-on-action” (Schon *1983*, *1987*) undertaken after the teaching practice is completed. Through reflection-on-action, the teachers realized the need for expansion or modification of their planning or repertoires for teaching a particular topic. As a result, they made additions to, reorganized, or modified their existing body of PCK for teaching the topic. In this regard, the development and enactment of PCK was a stable and static process.

In Amy’s metal lab, the same incident that happened in Lucy’s lab occurred, that is, the zinc shattered. Unlike Lucy, Amy did not mention the incident during the lab, though she noticed that it should not have happened. After the class, she reflected on the incident in this way:

One of the things I really thought about was safety in planning this unit, because the students were developing tests like heating the metals...So I gave them zinc in chunky pieces. When they were doing a test to see if it was malleable, it shattered. So now they’re under the mistaken impression that zinc is not malleable. So next year when I do this, I’ll give them each metal in different forms. I thought about giving the sheet metal to start with, but those edges are so sharp. I’ll cut them. I wish I had thought about it differently. (Amy, post-observation interview 1)

This statement provides a picture of how she planned to reshape her lesson to reconcile the conflict between safety and student misconception. After this reflection-on-action, Amy hammered chunky zinc by herself and realized that the chunky piece “appeared” brittle because they had little pieces that jut out and easily broke off. Then, she hit a little zinc piece and saw that it was malleable. She thought that if students had observed more carefully and taken the little pieces that had broken off, they could have seen that this zinc sample is malleable. With this understanding, she made an addition to her repertoire for the next class to confront the students' misconception about zinc developed in the lab. In fact, in the next class, she asked the students if they expected zinc to be brittle or malleable. No student was surprised that the zinc shattered. She showed them the chunky zinc and demonstrated to them how small pieces are malleable, though large pieces break up easily. With this result, she emphasized the importance of careful observation in scientific methods. She also showed strip zinc and demonstrated its malleability.

These two situations serve as brief examples but point toward the conclusion that PCK has both aspects of knowledge-in-action and knowledge-on-action. The two aspects were not mutually exclusive, but rather influenced each other through reflection, either inside or outside classrooms. As a result, reflection-in-action and reflection-on-action synergistically impact PCK growth in terms of knowledge-in-action and knowledge-on-action.

Teacher Efficacy: An Affective Affiliate of PCK

An in-depth analysis of explicit PCK revealed an ancillary aspect of PCK that was not anticipated based on our original conception of PCK from the research literature. After consistently finding an affective affiliate in 15 out of 20 examples of explicit PCK drawn from the multiple data sources, the label that best fit seemed to be teacher efficacy. Further characterization of this affect, confirmed its best descriptor was a highly subject specific version of teacher efficacy in that it was related to teacher beliefs about their ability to enact effective teaching methods for specific teaching goals and was specific to classroom situations/activities.

Our notion of teacher efficacy is drawn from the concept of self-efficacy that evolved from Bandura's (*1986*) social cognitive theory. One main idea of this social cognitive theory is that individuals' perceptions of themselves mediate their behaviors. Thus, individuals pursue activities and situations in which they feel competent and avoid situations in which they doubt their capability to perform successfully (Pajares *1992*). Along this line, when teachers believe their capability to execute their PCK effectively, the PCK will be more likely to be enacted in actual classrooms. Interestingly, while attending a recent conference, we learned that Appleton (personal communication, January 14, 2006) had applied the label of "teacher confidence" to a similar finding of an affective component of PCK. In a related publication, he described this component of PCK as "an attitude cluster, rather than what is traditionally considered as knowledge" (Appleton *2006*, p. 42) and considered it be a "critical influence" on the science PCK of elementary teachers.

Lucy's post lab discussion after the metal lab provided a representative example of how teacher efficacy plays a role in the enactment of PCK. Before the post lab, Lucy described how she would lead the class to challenge students' misconceptions associated with the properties of elements and compounds. She said,

I have some [knowledge of] misconceptions that usually occur. There are some [misconceptions] that I think will happen [in today's class]. So I'll listen for them and if they seem to have it, but I'm not quite sure, I will ask a question to see if they have the misconception that will trip them up. And I'll try to get them to think about it from a different angle so that they can correct their own misconception. I'm quite skilled in that. (Lucy, pre-observation interview 2)

During the post lab, this self-perceived confidence enabled Lucy to confront students' misconceptions and stimulate conceptual changes. When a student asked whether copper carbonate is conductive or not, she sensed that some students might hold the misconception that when an ionic compound contains a given metal, it has all the properties of that metal. This was one of the common students' misconceptions she had previously discovered. Thus she asked a series of questions such as whether rust would have any properties of a metal because iron was a part of the compound. Moreover, in order to push students to consider whether they hold the misconception that ionic compounds never conduct electricity, Lucy initiated a discussion about conductivity, asking why iron (III) oxide did not conduct electricity when tested as a solid compound in a past lab. Then the subsequent discussion led the students to understand that ionic compounds conduct electricity when they are dissolved in water. These two examples showed how Lucy's teacher efficacy promoted her movement from understanding of students' common misconceptions to action transformation (Woolfolk et al. *1990*). After this post-lab, Lucy said,

I got a lot of evidence [that] I supported the kids getting correct concepts. I tried to go with them in their thinking and show them where they might have gotten off. Did it change their mind about one part of how they were thinking? Yes, I was able to correct their misconceptions. (Lucy, post-observation interview 2)

From this statement, it appeared that her teacher efficacy was strengthened through successful teaching experience. Research has shown that higher teacher efficacy encourages the establishment of worthier professional goals and manifests as a willingness to try new teaching strategies (Guskey *1988*). Conversely, greater success in the classroom, which in turn stimulates higher teacher efficacy (Ross *1995*). This study does not provide extensive evidence that teacher efficacy affects actual teaching practices. Based on other research (e.g., Stein and Wang *1988*), however, it can be expected that Lucy's enhanced teacher efficacy might facilitate her acquiring and implementing new teaching strategies, which might foster her PCK and effectiveness, thereby increasing her teacher efficacy even more.

Meanwhile, teacher efficacy appeared to be domain specific (e.g., subject matter vs. pedagogy). While Lucy manifested a high level of teacher efficacy in getting students directed toward a valid understanding of science concepts, she felt that she was less efficacious for having the students take notes of what they learned. She confessed,

I often have a hard time to have the kids take the notes. I don't have the skills needed to train them that way. I know they need to learn how to study to succeed in college. But I don't think I am good at doing that...I don't ask them to take notes much. (Lucy, pre-observation interview 3)

Lucy's teacher efficacy in challenging misconceptions did not transfer to her belief about her ability to make students effective note takers. Teacher efficacy is a specific rather than a generalized expectancy. This characteristic is compatible with the domain and topic specific nature of PCK.

Impact of Students on PCK

Student impact on PCK as a result of formal and informal assessment data has been suggested (Shulman *1987*), but this study points to three direct means through which students affected teachers' PCK development. First, when students posed challenging questions to teachers, these questions frequently facilitated both deepening and broadening of the teachers' subject matter knowledge. Adequate subject matter knowledge is a criterion for PCK development (Van Driel et al. *1998*) and these acts of deepening and/or broadening subject matter knowledge increased the teacher's accessibility to the reflective actions through which PCK is developed. The teachers often encountered students' questions about which they did not possess subject matter knowledge in a form from which answers or even a means to construct answers through student activities were known. Thus, these questions "made them look for things and questions that have never occurred to them" (Jane, Post observation interview 1). And these encounters led to a transformation of the subject matter into a form that could successfully be used for teaching.

An example was captured in the middle of Lucy's "chemical compound" lab in which students were asked to identify given unknown compounds. On the first day of the lab, Lucy visited each group and asked how they would design a test, collect data, control variables, and use their results to identify an unknown compound. One group of students said that they would use a flame test. Prior to allowing students to proceed, Lucy wanted to confirm that the students understood that a flame test showed the colour of a metal ion. She asked the students a few questions to assess their understanding, but was surprised by one student's interchange. It began when a student questioned why the colour of the non-metal anion did not interfere with the visible emission spectrum of a metal cation. Lucy replied, "That's a great question, I've never thought of it. I should figure that out" (Lucy, Classroom observation 7). She researched the question after class and created a means for how she would facilitate students' understanding of energy level and wavelength in a subsequent instructional session. She later reflected on this incident in this way:

It was interesting that the question about anions had not come up during the flame test lab earlier in the semester. I researched it that night and was able to tell them next day that anions usually emit waves in the invisible ultraviolet range. Also, I was able to strengthen [their] inquiry by questioning them about whether electrons in an anion might also get excited and emit energy. They had to apply knowledge of visible and invisible electromagnetic waves to pose an explanation. (Lucy, written reflection)

This reflection shows how the act of responding to challenging questions resulted in Lucy's subject matter knowledge being deepened, and she was able to develop relevant productive questions to enhance students' inquiry about energy levels and wave lengths with the result that her PCK for that specific topic was broadened.

A second means through which students influenced teachers' PCK resulted from the informal assessment of students' participation in class. Students' responses such as enjoyment, evidence of learning, and nonverbal reactions to instructional strategies affected teachers' decisions to replace, modify, or validate the strategies employed. In the "chemical compound" lab, Lucy assigned student groups to create PowerPoint presentations as a means for all groups to communicate their results with one another. But when the presentations were made, she sensed that students were bored by them. Through her reflective process, she analysed why students responded in that way and decided for the next school year, she would replace the PowerPoint presentation assignment with what she called "wanted posters." She wrote in her reflective journal:

I realize that if all analysis and concluding have been already done, it can feel as if they are just going through the motions to get their final grade (gag) [teacher's written comment to show her disgust]. The trick is designing a method of presenting that continues to engage kids in active and authentic inquiry. The next time I teach this I will have groups make "Wanted" posters which will include a suspect, identification of their compound, and all the supporting data/research that leads to their conclusion. (Lucy, written reflection)

While Lucy revamped her instructional strategy, Amy validated her new strategy through interaction with students. Amy planned and implemented a new unit called the "Statue Unit" to teach elements and compounds as an inquiry-oriented approach. In the Statue Unit, students were asked to make a decision on which combination of metals was best among the four given statues. Their choices were to be based on the chemical and physical properties of the elements composing the statues and ascertained through a series of student-designed investigations. Throughout that unit, she observed that her "difficult-to-teach" students actively engaged in the lab and assignments. She measured this engagement informally, but consistently believed that students who did not typically become involved in science lab activities were involved under these classroom circumstances. This served for her as a validation that this new strategy worked. She described it in this way:

Those students are usually likely to rebel against assignments. But in this assignment, boom, what they gave was really what I was looking for....They did have a chance to shine in this lab, because they got to use their good thinking and apply it. I have a girl who is not motivated to do labs and work on routine homework. But, she came to me and said "I did a good job in lab!" with excitement....It worked. (Amy, post-observation interview 3)

This validation enhanced her instructional decision to implement the same strategy next time, as shown her statement that "I will keep doing this inquiry unit because that proved truly powerful to teach properties of elements and compounds" (Amy, post-observation interview 3).

Students' responses sometimes motivated the teachers to expand or enrich their instructional repertoires as well as validate them. In the first phase of the Statue Unit, students were asked to read selections from their texts and to develop lab tests to determine the different properties of the elements that would help them choose the best statue. While students were carrying out the lab tests that they designed, Amy realized that some of the students had not read the text or had not made adequate connections between the reading and the lab. She also recognized that most students focused just on physical characteristics such as colour, density, melting point, durability, and conductivity and collected quantitative data. Thus, Amy made additions to her original lesson plan in the following way:

I created and administered a 25-question quiz to ensure they understand the core content in the reading assignment. In the future, I'll give the students the 25 content questions to answer prior to the lab activity to ensure they get the content. Also, I'll change the rubric to include a required number of physical and chemical tests instead of leaving it open ended, so students will not focus just on physical changes. But, I'm not going to specify which ones to do. (Amy, post-observation interview 2)

This passage implies that Amy reconstructed her instructional strategies for the Statue Unit through interaction with students, integrating her knowledge of curriculum (i.e., what are goals and objectives in this unit), knowledge of students' understanding and learning difficulties, and knowledge of strategies for assessment (i.e., the use of rubrics). Given the results of these encounters with these domains of knowledge which are major components of PCK, we concluded that Amy expanded her PCK.

A third means by which students impacted the teachers' PCK resulted from the observation that students' creative and critical ideas stimulated teachers' creation of innovative instructional ideas for future classes. In Lucy's class about chemical compounds, she and her students were discussing why each of the groups had gotten such disparate density data for the same chemical compound. One student, Sherry, stated that she discovered that a solid compound had different densities depending on whether it was hydrated or anhydrous, and this could be a reason for the different densities across the groups. This student's idea inspired Lucy's plan for a future inquiry lab. In her written reflection, she asserted,

I realized that Sherry's findings of different densities for hydrated and anhydrous salts would make a great inquiry lab for future classes. Students would be given a compound and have to find its density, its water of hydration (calculate percent composition and construct empirical formulas), and the density of the compound in its anhydrous form. (Lucy, written reflection)

Without the student's input, Lucy might not have thought of this new approach for a future lab. As a result, her body of PCK was expanded with the idea of this future lab. Overall, students played vital roles in determining the ways that PCK was shaped, developed, and validated.

Students' Misconceptions: A Major Factor that Shaped PCK

Interestingly, all participants perceived that a major goal of teaching science was to connect what students learn with their everyday lives. To this end, the teachers primarily stressed students' conceptual understanding rather than their acquisition of factual knowledge, because they believed that deep understanding of a concept is essential for students to "relate their understanding to a bigger world than just their classes" (Lucy, post-observation interview 1). In this regard, the teachers focused on monitoring, redirecting, and challenging students' misconceptions since they perceived that misconceptions were a major barrier to further understanding. Consequently, the teachers placed a great emphasis on students' misconceptions in both their planning and enacting of lessons.

For instance, Jane's focus on students' misconceptions was realized in her planning, teaching, and reflection. Before a class that dealt with atomic structure, she expressed concern about possible students' misconceptions related to this topic:

I'm afraid they don't realize just how small the nucleus is in relation to the rest of the atom. The electron, you know, [has] very little mass, but is zipping around all over the place in a very large area of space...it's a cloud. And then when we on the board just draw it nice and rigid like it's a circle, I'm afraid that's what they think. (Jane, pre-observation interview 1)

This concern stimulated her to develop a simile to explain electron configuration. In the class, she said,

When we talk about an electron cloud, I want you to envision...a fan. When a fan is turned on, the blades are going so fast, you can't tell exactly where the blade is at a particular time. It just looks like it's everywhere. It's the same way with the motion of the electrons. They're moving around so fast, it's hard to pinpoint its location. (Jane, observation 1)

Right after this explanation, a student asked a question, "Are electrons circling around the nucleus?" From this question, Jane noticed that the simile of a fan spinning led students to the misconception that electrons were circling like planets around sun. Thus, she introduced an analogy to make sure that we can never be certain of an exact route or position for an electron:

I'm going to use you as an example for trying to find electrons. Let's say we're trying to find you in Georgia. To narrow down the view a little bit more, I would say the county, Lanier. To narrow the view a little bit more, I would say the city, Seville. And [we do] not know exactly that you're sitting here in Chattahoochee River High School in this desk, we can't pinpoint exactly where you are because you're moving so fast and randomly, but I could know that you're in here somewhere during fourth period....That's the same thing that quantum numbers do for being able to tell us about electrons. (Jane, observation 1)

Although Jane did not plan to use this analogy, when she had to deal with expected students' misconceptions, she elicited the analogy from her repertoire because it characterized how she "has been able to pretty effectively communicate to the students the content" (post-observation interview 1). Reflecting on the use of the analogy, Jane expressed the need of more sophisticated PCK to make students understand the concept of quantum numbers:

Perhaps the analogy is a good hook to get them to be thinking about what quantum numbers are, and why that's important....But at the same time I can see where it might be a distracter if the analogy isn't further [supported]....Since that [quantum numbers] is such a hard concept to wrap your mind around and such a huge factor of which everything else hinges on in chemistry that it would be worth spending more time on than just oh, this is an analogy. (Jane, post-observation interview 1)

This statement suggests that Jane's understanding of students' misconceptions affected her planning and enacting of teaching a particular topic and as a result her PCK expanded.

Moreover, students' misconceptions was a major factor that the teachers took into consideration in determining the content of assessment. As an illustration, in the "metal lab" of Amy's honours class, a group of students exposed their misconception that all the tests they were doing to determine the properties of the metal samples, even conducting reactions with acids or fertilizer, included only physical changes. Meanwhile, in Lucy's gifted class, it became apparent that some students thought that HCl (hydrochloric acid) was the main chemical agent in acid rain. This conception resulted from using HCl to test how each of the metal samples reacted when exposed to a simulated acid rain. Although Amy and Lucy confronted those misconceptions immediately when they uncovered them, they wanted to ensure that the students ultimately constructed informed conceptions. Consequently, they modified the content of their lab assessment adding problems related to chemical changes vs. physical changes and chemical reactions of metals with acid rain. As shown in this case, assessment served as a means both to monitor and challenge students' misconceptions.

In summary, teachers' understanding of students' misconceptions impacted their decisions made throughout the entire teaching process from planning to assessment, which ultimately improved their PCK. As teachers developed better understanding of students' misconceptions, their PCK became more sophisticated.

Idiosyncrasy in the Enactment of PCK

Although the PCK of the three teachers had common characteristics, their PCK was also idiosyncratic. Amy, Lucy, and Jane collaboratively developed a chemical reaction unit called the "Mendeleev Manor." This unit was a 6 week inquiry designed to teach chemical reactions through a lifelike laboratory scenario. The teachers individually implemented the unit in their honours or gifted chemistry classes. Thus, it was possible to discern instances of unique enactment of instructional strategies while they were teaching the same unit. The enumerative analysis using the PCK ERT (see Appendix A) revealed that the teachers used similar instructional patterns across some of the categories, but distinctive patterns also appeared for each teacher within certain subcategories of instructional strategies and representations. Each teacher had moments when they had to answer students' questions, explain subject matter, summarize discussions throughout this unit and so forth. Differences in enactment often resulted from these moments of "responding" to events within instruction. What factors shaped the idiosyncrasy of these teachers' PCK? Analysis pointed to four factors: (a) orientations to science teaching, (b) characteristics of students, (c) teaching experiences, and (d) personal characteristics.

Amy had taught College Preparatory (CP) chemistry more than 20 years. She had come to realize that making subject matter "clearer" to students was necessary for scaffolding those students' conceptual understanding. Accordingly, she strove to develop specific strategies using relational terms and tools. Those strategies had become a part of her teaching expertise and for her, are robust for a wide variety of students and across topics. She illustrated the motivation to use these relational strategies when she described her shift from being a traditional "straight fact" teacher for the CP chemistry students.

Although most CP students will not major in science, they need to have an understanding of chemical concepts and how to use these concepts to make informed decisions in order to be responsible citizens. At one time, I was very traditional, and I taught just straight facts. And, I found that they weren't retaining it. So I really started trying to find ways to make things clearer and more understandable to students. I've always done a lot of comparison and contrast and getting charts together. I always kind of go through a pattern. (Amy, post-observation interview 3)

Her representational strategies evolved from the relationship among her beliefs about the goals of teaching science, the characteristics of her students, and her teaching experience.

With the overarching goal of improving students' conceptual understanding, Lucy focused on improving students' thinking skills. This emphasis was apparent in the catchphrase hanging on the front wall in her classroom: "The single most important thing you can bring to this classroom is your own good thinking!" She encouraged students' logical reasoning, even if it led to the wrong conclusion, because she wanted to convey to her students that "Thinking is welcome here!" and "Using scientific habits of mind over random guessing is valued" (Lucy, post-observation interview 2).

In order to foster students' thinking skills, Lucy believed that discussion was the best pedagogy, because "discussion is thinking out loud; it gives students the freedom to go in depth rather than just cover many topics in brief; it enables students to both demonstrate and witness logical scientific thinking" (Lucy, written reflection). Thus, discussion, argument, and questioning came to constitute her favourable instructional strategies over time.

In addition, Lucy had taught gifted chemistry since she started teaching. She has never taught CP chemistry. Her perception of the characteristics of gifted students and her emphasis on thinking skills enhanced her use of discussion. She said:

My gifted students are curious, like to ponder issues on a deeper basis, and like to find unique ways to solve problems. In order to satisfy their curiosity and focus their energy....I frequently use inquiry labs and class discussion. My students are quite skilled in these areas. They probe each other in lab and in discussion, feeding off each others' ideas. (Lucy, written reflection)

Her preference for discussion and argument has developed over time through a combination of her understanding of gifted students and their educational needs along with her beliefs about teaching science.

This idiosyncratic aspect of instructional strategies and representations was demonstrated somewhat differently in Jane's practices. Jane's use of visualization was mainly informed by her personal learning characteristics. She conceived of herself as a visual learner because she was able to learn better from drawings or writings. Further, she believed that her preference for visualization as a learner resulted in her frequent use of visualization as a teacher. She frequently drew pictures, concept maps, or flow charts. During whole class discussion, she used figures, drawn on her white board, to create a summary of what students said.

The explication of these idiosyncratic characteristics illustrates how teaching can be a complex cognitive activity, as well as being highly context and topic specific. In this study, the three teachers demonstrated their idiosyncratic repertoires when they were teaching co-constructed unit plans (e.g., Mendeleev Manor). However, this does not imply that each teacher's strategies are fixed. Indeed, application of teachers' knowledge is dependent on context and interaction with students.

This claim was supported by other analysis. The teachers each asserted that misconceptions needed to be addressed immediately because they hinder students' further understanding. Therefore, the teachers challenged them as soon as possible. However yet there were times when they did not address the misconception that had been uncovered. Rather, the teachers allowed time for students to work through their own conceptions and used their misconceptions that the teacher noticed in shaping the whole group discussion. Lucy felt that in some instances this resulted in greater clarity for all students.

This example demonstrates how idiosyncrasy occurs within the practices of a single teacher. She normally responds to students in one way (e.g., challenges misconceptions), but sometimes she does not. Idiosyncrasy is also seen across individual teachers' PCK who have planned together. Taken together the two types of idiosyncrasy are another support for the idea that PCK is a special body of teachers' knowledge necessary to successfully perform teaching within complex and varied contexts. Furthermore, this description of idiosyncrasy signifies that there is no single right PCK for teaching a particular topic. We believe that establishing idiosyncrasy as an aspect of the nature of PCK is an aid to clarifying the complexity of teaching.

Discussion

The data analysis validated, refined, and identified new components of PCK that were revealed from the literature review. Specifically, this research has contributed three new features and offered clarification of two other features within the collective model of PCK found in the literature.

One new characteristic of PCK arose from recognition of the synthetic and synergistic impact of both knowledge-in-action and knowledge-on-action on PCK. This interrelationship implies that PCK development encompasses knowledge acquisition and knowledge use. It is unlikely that teachers acquire PCK first, and then enact it. Rather, knowledge acquisition and knowledge use are interwoven within the context of instructional practices (Eraut *1994*). Teachers develop PCK through a relationship found amid the dynamics of knowledge acquisition, new applications of that knowledge, and reflection on the uses embedded in practice. This assertion also supports the idea that teachers do not simply receive knowledge that others create to teach, but produce knowledge for teaching through their own experiences. Although teachers' knowledge can be influenced and improved by receptive learning, the most powerful changes result from experiences in practice. Teachers are knowledge producers not knowledge receivers. This characteristic is essential to view teachers as professionals.

Since the enactment of PCK within a given lesson requires a teacher to integrate different components of PCK and since each teacher develops those components as a result of different experiences and knowledge, teachers' PCK is idiosyncratic to some degree. Individual teachers' idiosyncratic PCK appeared to be continuously changing and reconstructing as it became an established aspect of their achieved PCK. However, most importantly, this idiosyncrasy, characterized by teachers' autonomy and abilities with regard to the accession and generation of information and knowledge, is also a key attribute of teachers as professionals (Donnelly 2001).

This study was conceptually grounded in five components of PCK for science teaching. As a result of this empirical research, however, one new affective component of PCK, teacher efficacy, emerged. In that teacher efficacy refers to teachers' beliefs in their ability to affect student outcomes (Tournaki and Podell 2005), it is typically considered as a comparable component of belief, not knowledge. However, Kagan (1992) defined beliefs as a "particularly provocative form of personal knowledge" (p. 65) and concluded that belief is a form of knowledge. She further argued that most of a teacher's professional knowledge can be regarded more accurately as belief. Nespor (1987) emphasized the role of teachers' beliefs in defining teaching tasks and organizing the knowledge relevant to those tasks. In order to solve ill-defined problems that teachers often encounter (Richardson 1996), they need to go beyond the information contained in the problem instruction, re-examine knowledge they already have from multiple perspectives, and make assumptions or decisions (Nespor 1987). In this process, this more "affective" or provocative form of knowledge is playing an important role.

Given that the study of this affective component was not within the original intent of the study, we have linked it most closely to teacher efficacy and feel that it plays a critical role in defining problems and determining teaching strategies to solve the problems, therefore leading to the reorganization of knowledge. Taken together, it is reasonable to view teacher efficacy as a component of teachers' knowledge.

Moreover, in this study, PCK was conceptually defined as a construct consisting of two dimensions: understanding and enactment. Teacher efficacy served as a conduit to connect those two dimensions. Increased teacher efficacy had the result of providing encouragement for teachers to enact their understanding. When the enactment was successfully performed, teacher efficacy was in turn increased. The increased teacher efficacy renders the teachers ready to learn relative to any of the components of PCK, whereby their understanding is expanded (Stein and Wang 1988). The conclusion was reached that teacher efficacy is linked with PCK.

Another salient aspect of this research was that PCK was influenced by students' questions, critical thinking, verbal/nonverbal responses, and evidence of learning. In particular, teachers' understanding of students' misconceptions appeared to be a primary factor that influenced the teachers' PCK. This feature implies that teachers' capacity to "read" students is essential to their PCK development because students' responses can influence teaching practices only when a teacher is aware of their significance. Stated differently, only when teachers grasp their students' cognitive and affective status with regard to the learning of a particular topic can they apply pedagogically adjusted procedures in order to facilitate learning. Since teachers cannot always directly assess students' learning, they should learn to detect the signs of understanding and confusion, of pretended interest and genuine absorption. The teacher's capability to make these judgments and detect these understandings is grounded in subject matter knowledge and the components of PCK. When teachers develop the knowledge bases of PCK, they come to create personal theories and explanations based on them. Then those theories inform the teachers' instructional decisions and actions. The professional develops theories of action by which the profession is practiced (Argyris and Schon *1974*); this aspect of PCK also contributes to teachers' professionalism.

The emergence of teacher efficacy, the qualification of idiosyncrasy, the importance of reflection, and the recognition of the significance of students' roles as units within PCK led to an evolutionary modification of our heuristic model of PCK as shown in Fig. 2. In this evolved model, the concept of PCK represents not only teachers' understanding of how to teach subject matter effectively, but also the enactment of their understanding. We recognize that this model of PCK is not necessarily a working model from which a prescription for teaching can emanate. But there are very important conceptual aspects of this model which can serve as a conceptual tool for future research.

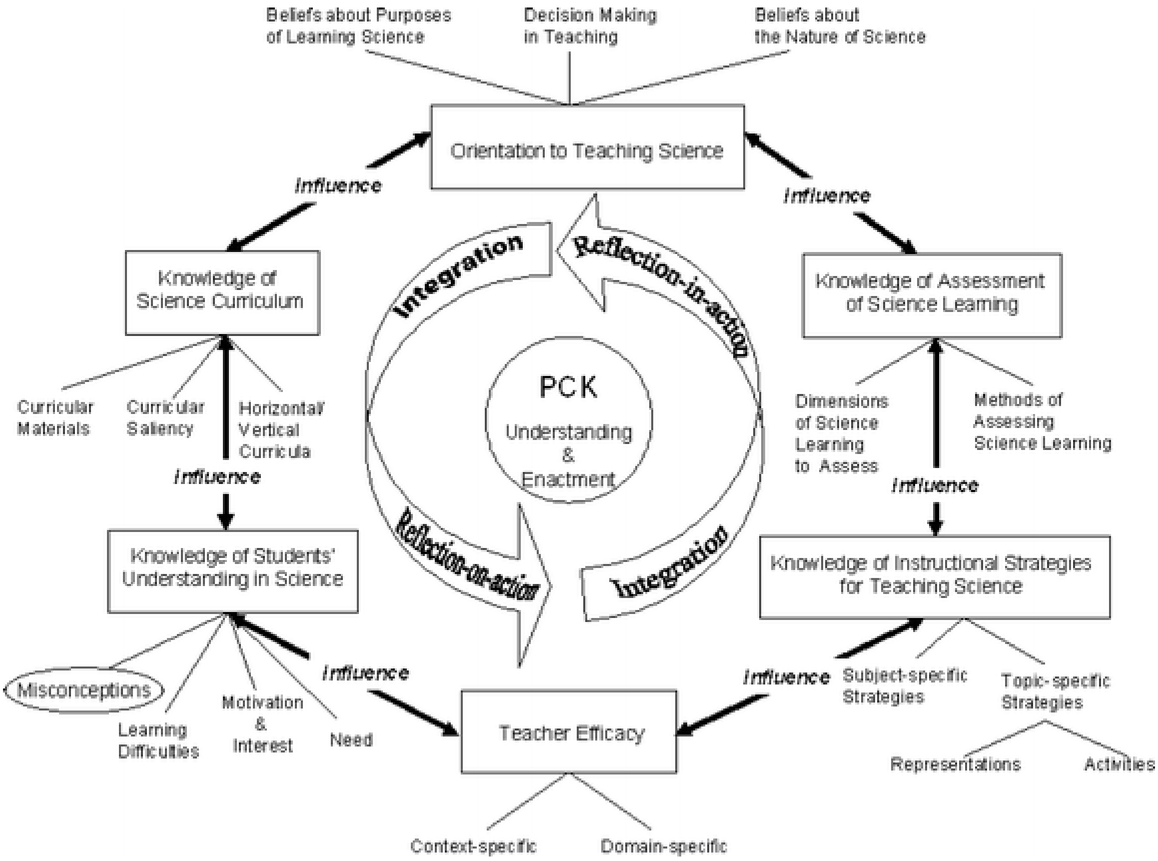

Fig. 2 Hexagon model of pedagogical content knowledge for science teaching

The six components influence one another in an ongoing and contextually bound way. In order for effective teaching to occur, teachers integrate the components and enact them within a given context. The integration of the components is accomplished through the complementary and ongoing readjustment by both reflection-in-action and reflection-on-action. This implies that as a teacher develops PCK through reflection, the coherence among the components is strengthened. This strengthening reinforces their integration, which in turn facilitates the growth in PCK and further changes in practice. We believe, however, that for some teachers, all outer

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components are in place but are lacking sufficient dynamic properties achieved through reflection. Thus the strengthening capability of the model may not be functional. Further, if a teacher is unable to integrate the components of the model in a coherent way, improvement within a single component may not be enough to advance PCK and therefore practice.

This refinement of the construct of PCK underscores that teachers are not simply doers; those who realize what others have planned. Teachers fill much of the school-related parts of their lives with planning, enactment, and reflection on instruction. At each phase, teachers continually assess their performance primarily based on interactions with students. As a result, teachers develop a body of knowledge unique to the members of the teaching profession. In this regard, it is PCK that is at the heart of teacher professionalism.

Implications

Based on our findings we suggest several implications for future research and science teacher education. This study ultimately proposed a conceptualization of PCK for science teaching which has two major attributes. First, the conceptualization has an interconnected set of six domains of teacher knowledge through which PCK is built. Second, the dynamic properties of PCK arise from reflection-in/-on-action. However, we still only minimally understand teachers' processes of integrating the domains into PCK and that guide their actions in practice. Research on this area is expected to contribute to a better understanding of the complexity of teaching and learning.

In order for the concept of PCK to be more useful, the assumption that PCK is highly related to students' learning should be further investigated. Recent work by Loughran and associates (Loughran et al. *2006*) and Hashweh (*2005*) move research on PCK in that direction. Given the significance of reflection on PCK development, understanding the relationship among a teacher's reflective capacity, PCK, and students' learning will provide a clearer picture of how students' learning relates to the knowledge and thinking carried by teachers.

Teachers' knowledge of students' misconceptions played a critical role in shaping PCK. Our finding of this result came from a study of teaching chemistry to high school students. Considering that subject matter courses are more central in secondary schools and secondary teachers are more subject-oriented than their counterparts in elementary school (Brookhart and Freeman *1992*), the nature of elementary teachers' PCK and its development might be quite different from the results of this study.

In that knowledge of students was essential for developing PCK, both pre-and in-service teacher education programs should provide opportunities for teachers to examine or analyse students' understanding, reasoning types, misconceptions, learning styles, motivation, etc. Research has suggested that students' misconceptions are more easily recognized when a teacher has a richer understanding of the content topics and concepts (Van Driel et al. *1998*). In this regard, pre-service teacher education needs to place more emphasis on the sufficient subject matter preparation in combination with extensive practicum in schools.

Ultimately, our conceptualization of PCK stresses the importance of coherence and

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integration among the six components of PCK for effective teaching. Teacher educators, whether working with pre-service or in-service teachers, need to be aware of the interrelatedness among the components, even when they focus on only one. At the same time, it should be acknowledged that reflection is a major vehicle to improve teachers' skills to integrate the components of PCK. Likewise, our model suggests that consideration of teachers' affective domains as well as their cognitive domains is important.

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